Background Material
for

South Asian Regional Workshop
on
Research Agenda for
International Human Dimensions of
Global Environmental Change Programme
Industrial Transformation (IHDP-IT)
April 4-5, 1998, New Delhi, India

Organised by
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South Asian Regional Workshop on Research Agenda for IHDP-IT
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Organised by
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at
Casuarina, India Habitat Centre
Lodhi Road, New Delhi-110 003, India

Program

4 April 1998 (Saturday)

0830-0900 Registration

0900-0905 Welcome by Dr R K Pachauri, Director, TERI, New Delhi, India.

0905-0915 Introduction of the IHDP-IT by Prof. Pier Vellinga, Director, Institute for Environmental Studies, Netherlands.

0915-0930 Inaugural address by Mr S S Boparai, Secretary, Ministry of Non-conventional Energy Sources (MNES), Govt. of India.

0930-0955 First Keynote address by Dr R K Pachauri, Director, TERI, New Delhi.

0955-1010 Tea break

Session-1 International issues related to IHDP-IT

Chairperson:	Prof. Robert H Socolow, USA
Panelists:	Prof. Pier Vellinga, Netherlands
	Mr Katsuo Seiki, Japan
	Dr Kulthorn Silapabanleng, Thailand
	Mr Brian A D Egan, South Africa

1010-1040 Second keynote address and discussion on "Framework for Industrial Transformation" - Prof. Pier Vellinga, Director, Institute for Environmental Studies, Amsterdam, The Netherlands

1040-1120 Third keynote address and discussion on Macroeconomic Incentives - Dr Shreekant Gupta, Delhi School of Economics, Delhi, India

1120-1200 Fourth keynote address and discussion on Technological change - Prof. R H Socolow, Director, Center for Energy and Environmental Studies, Princeton University, Princeton, USA.

1200-1240 Fifth keynote address and discussion on Consumption of Energy and Materials - Dr Leena Srivastava, Dean, Policy Analysis Division, TERI, New Delhi, India

1300-1400 Lunch

Session-2	**Asian Perspective on IHDP-IT**
1400-1615	Panel Discussion on "Issues in Industrial Transformation and Research Agenda for Asia"
	Chairperson: Prof. Pier Vellinga, Netherlands
	Panelists: Dr Ijaz Hossain, Bangladesh; Dr Sitanon Jesdapipat, Thailand; Mr Sadiq Malik, Pakistan; Dr S Maudgal, India
1500-1515	Tea break
1515-1615	Panel Discussion on "Issues in Industrial Transformation and Research Agenda for Asia" continued
2000-	Reception & Dinner

<u>5 April 1998 (Sunday)</u>

Session-3	Development of Research Plans and Priorities both for Asia and the World
0930-1230	Working groups
	Group-1: System Analytical Perspectives (Chairperson - Dr Leena Srivastava, TERI)
	Group-2: Industrial ecology (Chairperson-Prof. R H Socolow, Princeton University)
	Group-3: Consumption and Organisational Aspects (Chairperson - Prof. Pier Vellinga, Institute of Environmental Studies)
1045-1100	Tea break
1230-1330	Lunch
1330-1400	Presentations by the working groups on summary of discussions (10 minutes each)
1400-1500	Plenary session - Implementation strategies and plans
	Chairperson: Dr R K Pachauri, India
	Panelists: Prof. Pier Vellinga, Netherlands; Prof. R H Socolow, USA; Dr Ijaz Hossain, Bangladesh; Mr Katsuo Seiki, Japan
1500-1530	Tea
1530-1600	Summing up

Background Material
for

South Asian Regional Workshop on
International Human Dimensions of
Global Environmental Change Programme
Industrial Transformation (IHDP-IT)

April 4-5, 1998, New Delhi, India

Contents

1. Industrial Transformation: Research Directions
2. Industrial Ecology: Some Directions for Research
3. Industrial Transformation in Asia-Emerging Issues for Further Research
4. Dematerialisation and Rematerialisation
5. Hydrogen production from coal and coal bed methane, using byproduct CO_2 for enhanced methane recovery, with CO_2 sequestration in the coal bed
6. Prospects for reducing GHG Emissions in coal systems
7. Fuel cells, coal and china

Industrial Transformation

Research Directions

Draft Version

IHDP

February 1998

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Contributing authors: Edgar Hertwich, Eric Welch, Sander de Bruyn, Stefan Anderberg, Friedrich Hinterberger, Nese Yavuz, Aldo Femia.

IHDP-IT no. 10

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Preface

Dear Reader,

Industrial Transformation has been identified as one of the six priority research themes of the International Human Dimensions Program (IHDP) of Global Environmental Change. The ultimate aim of research on Industrial Transformation is to understand the human drives and mechanisms that could enable a transformation of the present system of production and consumption into more sustainable directions and in physical terms to decouple the growth in economic activities from the parallel growth of environmental pressures.

The present paper is a modified version of an earlier draft paper called Research Inventory. As to reflect that such an inventory would never be able to cover the entire field of research that could be relevant for transformation the title was changed to Research Directions. The present version is not complete yet. To support the regional workshops a partly updated version has been made. This version is now presented to you for comments.

This Research Directions paper as now being developed serves as a basis for the development of the IHDP-IT Science Plan. The frame work of this Science Plan has been endorsed by the first meeting of the Science Planning Committee in February 1998. The Framework for the Science Plan, together with this Research Directions draft paper will be discussed at the eight Regional Workshops to be held in the period March to October 1998.

The results of the Regional Workshops will be used as input for the Science Plan and the Global IHDP-IT Conference to be held in Amsterdam on February 24-26 1999.

The present version should be seen as a living document as additional changes from the members of the Scientific Planning Committee continue to come in.

Pier Vellinga

Chairman IHDP-IT Scientific Planning Committee

February 1998.

2. 1. Introduction: an exploration of research relevant for Industrial Transformation

2.1 Background

The International Human Dimensions of Global Environmental Change Programme (IHDP) fosters research-related activities that seek to describe and understand the human role in causing global environmental change and the consequences of these changes for society. IHDP was initiated in 1990 by the International Social Science Council in order to complement research conducted by natural scientists in the International Geosphere Biosphere Programme (IGBP) and the World Climate Research Programme (WCRP). From its inception, the IHDP was conceived as a comprehensive, interdisciplinary and international framework for research on social processes relevant to global environmental change. At present, IHDP is developing a research framework that emphasises the dynamics of the human driving forces of change and the socio-cultural and institutional influences on these forces. This international programme is characterised by an emphasis on those processes that are universal and cumulative or that transcend regional or national boundaries and seeks to integrate and stimulate co-operation among international and interdisciplinary scientists by establishing both a network and a platform for communication and discussion.

2.2 Scoping

Industrial Transformation (IT) has been identified as one of the six priority research topics within IHDP. After the international IHDP-IT conference, held at the Institute of Environmental Studies (IVM) in Amsterdam, January 1996, a small group has drafted the Scoping Report, hereafter SR (Vellinga et al., March 1996). The SR aimed:

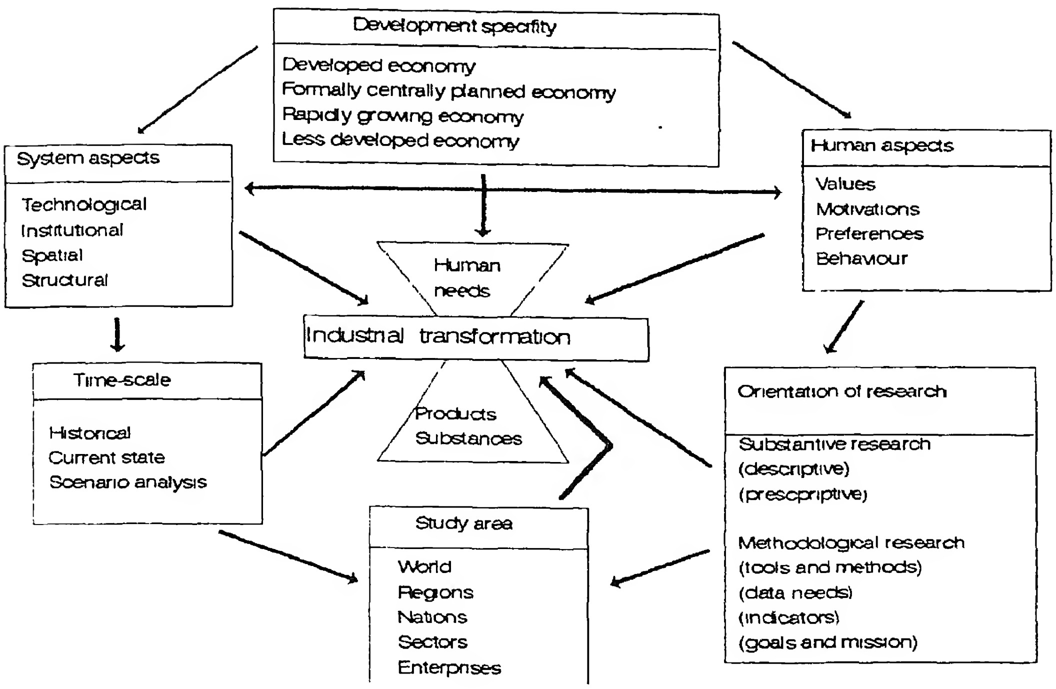
"to provide the elements and insights necessary to develop and interdisciplinary research program. Such a research programme, to be developed in the next stage, will be achieved by priority setting and a refinement of the Scoping Report, complemented with a thorough inventory of ongoing research".

The main contribution of the SR to the international research community has been the delimitation of the research area and the identification of possible research entries that could be chosen in IT-related research.

The study of Industrial Transformation undoubtedly requires interdisciplinary research. Different disciplines have started to investigate parts of the research on Industrial Transformation, and new interdisciplinary research areas have emerged on a limited scale (such as industrial metabolism, industrial ecology, ecological economics). This research has resulted in some new insights and analytical tools, such as life-cycle analysis and material balances, but gaps and deficiencies in research abound.

The integration of several scientific disciplines around the topic of Industrial Transformation requires an identification of certain angles or approaches of research. One way of integration is to focus on certain substances (including materials, energy, emissions, and wastes) or products. Another way is to focus on basic human and societal needs, that motivate industrial activity. Industrial production is not an accidental process, but is ultimately driven by human and societal needs. Human and societal needs do not necessarily relate directly to industrial activities: human activities relate to survival and to certain valuable things in life such as affection, power, security, peace of mind and pleasure. Needs can then broadly be defined in terms of basic needs such as nutrition, shelter, clothing, education, health or clean drinking water, or in terms of wants, i.e. diversity of food and clothes, consumer durables etc. Needs also enclose intangible assets, such as broader conceptual terms of welfare, well-being, human rights, peace and self-realisation (for example through employment). These needs in its broadest sense drive, individually and collectively, current industrial development/ transformation and will also drive future Industrial Trans-formation. Figure 1 provides a range of other choices for entries of research in the field of Industrial Transformation. Each box represents a choice for the orientation of specific research programs:

- system aspects,
- human needs and societal aspects;
- development stages;
- time scales;
- geographic/ sector specificity; and
- conceptual orientation;



In formulating a research project, a selection of one or more topics in each box is required

The basic question put forward in the SR is how industrial development, production and consumption, can be made sustainable:

"The ultimate aim of IHDP Industrial Transformation is to understand the human drives and mechanisms that could enable a transformation of the industrial system towards sustainability, and in physical terms to decouple industrial activities from their environmental impacts".

2.3 Narrowing down the field

The field of research that could be of relevance for Industrial Transformation is very broad. In order to create a practicable basis the issue of transformation has been framed in a specific and by definition arbitrary way. An important starting point for the framing has been the notion that such an international research plan should create a bridge between the natural and the social sciences involved in environmental research. Moreover this IHDP program should bridge the paradigms in technological research and the paradigms in economics and social sciences research. Transformation, thus change is the key word for the research activities to be explored. However change and the notion of change is directly related to the notion of scale with regard to the numbers of actors considered, the geographic scale and the time scale. An early consideration in the present document has been the desire to

encompass both the top down approaches in transformation research (macro economists, material flow analysts) and the bottom up research (consumer behavior and organizational matters at firm level). This approach helps to handle the vast field of potentially relevant research, however it also acts as a filter as some relevant research areas may fall between the cracks of the structure adopted. This is recognized as the price to be paid for a clear and coherent research plan.

Based on the consideration mentioned above the present paper addresses the field of potentially relevant research by the following three fields of research:

- Research that deals with the macro environment in which producers and consumers operate: this includes research on the changes in (macro) flows of substances, materials and energy and research on changes in the (macro) incentive structure guiding these flows;
- Research that deals with the production system, thus focusing on technological change and changes in the organization of production;
- Research that deals with the consumption system, thus focusing on (changes in) needs and preferences and changes in the ways needs and preferences are expressed.

The relation with the global environmental issues as described and studied by the natural science community is developed by focusing on substance, material and energy flows as affected by industrial activities. Industrial activities are meant to include both the production and the consumption system.

This report starts with a description of present day research activities related to the first category mentioned above: the macro system and incentive structure, this is chapter 2. The third chapter deals with the production system and the fourth chapter deals with the consumption system.

The first field focuses on disciplines such as macro economics, resource economics, geography, political sciences and public administration. The second field focuses on disciplines such as technological research, technology assessment, business administration, micro economics, environmental accountancy and sociology of the firm. The third field focuses on disciplines such micro-economics, psychology, anthropology and political sciences. There are many more disciplines involved in studying industrial activities and their relation with the environment. Moreover each of the

disciplines mentioned above is usually active in more than one of the three fields identified. The authors of the present document are aware of the fact that structuring it goes with choices that are sometimes arbitrary. We hope the readers will understand the arbitrary-ness of some of the choices that have been made in putting this report together. Still we encourage all researchers interested in the field of industrial transformation to put forward ideas and proposals that can help to improve the present document.

2.4 The development of integration in social and natural sciences

One of the central aspects of any human dimensions program on environmental change deals with the analysis of society and its development from an environmental point of view. Such analysis requires interdisciplinary research. By now there is some experience in integrative efforts between social scientists and natural scientists. One example of is the development of environmental sciences as a multi-disciplinary research field. Starting from the ecology perspective that studied organisms and ecosystem behaviour, geographers added to the field during the 1950s by, for example, investigating the potential space and energy resource base for economic activities (Hubbert, Vogt). During the 1960s, biologists made their contributions to this field (Carson and Ehrlich) by pointing out at the dynamics of carrying capacities to f.e. population growth, using often Lotka-Volterra types of logistic curves. During the early 1970s, engineers and computer scientists added to this by building computer simulation models (Forrester, Meadows) and economists added to the debate by pointing out at the physical exchanges between the economy and the natural subsystem (Daly; Georgescu-Roegen; Boulding; Ayres and Kneese). New fields include those of psychology, sociology, history and linguistics.

Along this development and strengthening of inter-disciplinary research in the area of environmental sciences, social sciences have also included insights from the natural sciences. For example, in economics research on the interactions between the economic system and the eco-system has been facilitated by introducing concepts from the natural sciences. These include: the dynamics of animal-populations (Clark: carrying capacity in bio-economics); the first and second law of thermodynamics (Ayres/Kneese and Georgescu-Roegen) and, more recently, the concepts of evolution (Gowdy) and chaos (Nijkamp and Reggani). Such contributions have *not* led to a new grand theory on the physical exchanges between the economy and eco-systems of substance flows, but they resulted in general into a

restatement of the *limits of growth* and to theoretical refinements in, for example, the concept of the 'environmental utilisation space' (Siebert/Opschoor).

Starting from	Research field	Contains	Elements
Society	Macro Systems and Incentive Structure	Theoretical and empirical efforts on broad processes of societal change in the interaction of the environment and the economy with special emphasis on material, energy and substance flows	Integrated Assessment, Industrial Metabolism, Material Flow Analysis, Material Product Chain Analysis, Eco-restructuring, Ecological and Environmental Economics
Enterprises	Industrial Ecology (eco-efficiency)	Research aimed at improving the ecological efficiency of industrial production in specific firms (processes and products) to be achieved at lowest possible costs	Pollution Prevention, Clean Technology, Life Cycle Design, Loop-Closing , Life Cycle Analysis
Organisations	Organisations, Management and Networks	Research aimed at improving organisational design and understanding organisational behaviour from the perspectives of specific firms in combination with their wider socio-economic and environmental surroundings	Organisation theory, Environmental Management, Network Analysis
Consumers	Sustainable Consumption	Research aimed at understanding determinants of consumer behaviour and the associated environmental impacts from consumption	Determinants of consumer behaviour, Environmental Impact from consumption

Table 1: Distinguished research fields

Hence, despite the fact that much of environmental sciences is still mono-disciplinary and lab-related, there is a development towards integration of environmental sciences in the social sciences and vice versa. When such integrated efforts relate to the various aspects that accompany the (two-way) interactions between environmental change and the production and consumption of manufactured goods and services, it reflects research that we would label under the heading 'industrial transformation'. That is:

Industrial transformation may serve as an umbrella of various research efforts that address efforts in describing the patterns (over space and time), organisation and technology of production and consumption of manufactured goods and services, their material and energy transformations and associated environmental impacts and the consequences of these impacts for the quality of life.

The umbrella function of industrial transformation is important in this respect since IT is currently not recognised as a separate research field. One of the particular justifications of a research program on IT is to overcome the separation between the various research fields and to encourage interaction and eventually coherence between differing approaches that are currently established.

2.5 Identification of research efforts of relevance for IT

The loosely defined research field of industrial transformation, can be decomposed in various research efforts along different dividing-lines, or boundaries. Such boundaries hamper integration and communication between the various established research fields that have relevance for IT. The most important and powerful boundary is the difference between the so-called 'top-down' and 'bottom-up' approaches in IT-related research. 'Bottom-up' approaches in IT-related research share in common that they start from individual (groups of) actors that shape society and its environmental impacts. Enterprises are the central focus in the area of industrial ecology. Consumers and civil society are the central focus of the area of sustainable consumption. In contrast, 'top-down' approaches tend to view society as a whole with little differentiation towards various actors and a relatively poor understanding of, for example, behavioral aspects. Research fields in this area include industrial metabolism and integrated assessment. The distinction between top-down and bottom-up approaches is powerful and to overcome the dichotomy between both approaches is one particular justification for the development of a potential research field in the area of industrial transformation. The research fields of material flow analysis and life cycle analysis, for example, both have material and energy flows as subject, but whereas material flow analysis is dealing with material flows in spatially confined systems (countries, cities or sectors for example), life cycle analysis starts from individual products, often in individual plants.

This boundary between on the one hand top-down and bottom-up approaches and the various stakeholder-analysis in the bottom-up approach have been used to describe the research field of IT in this report. Several distinguished research fields have been unravelled by experts in the field which has

resulted in some background papers (de Bruyn and Anderberg, 1997; Hertwich, 1997; Welch, 1997; Hinterberger et al., 1997) that will be available through the secretariats of IHDP and IVM. These background papers describe in much more detail the various research fields and should be considered in combination with the present report.

The next sections summarise the individual reports/ background papers on the various research fields. Section 2 summarises the report written by De Bruyn and Anderberg on the Macro Systems and Incentive Structure (system-analytical aspects) with respect to IT. Research fields that are to be distinguished here include material flow analysis, industrial metabolism, integrated assessment and eco-restructuring. Section 3 describes the highlights in the area of industrial ecology and eco-efficiency, taken from the report written by Hertwich (1997). Section 4 presents a selection of issues from the report by Welch (1997) on organisations, management and network analysis. Section 5 describes, on the basis of the report by Hinterberger et al. (1997), the area of sustainable consumption.

In the January 1998 update, several changes are made to the revised version of May 1997. Some additional material has been added to and integrated in the Inventory. The thrust of chapter 3 has been refocused to a more pro-active perspective in order to capture the essence of the current discussions, which is to move beyond eco-efficiency. Furthermore, a new section on strategies for stimulating sustainable consumption has been added to chapter 5.

All of the Sections 2-5 contain an inventory of knowledge, research groups and communication channels that exist in the distinguished fields. The relation between political aspects and scientific research are also highlighted. In this inventory the relevance for IT of each distinguished field of research will be described and a number of research gaps will be identified. In Section 6 the justification for a research program on IT is discussed and promising areas of research are suggested. In the Annexes several related topics will be discussed. Annex 1 contains an overview of the existing networks among scientific, international governmental and non-governmental groups to which the IHDP-IT program may be linked. In Annexes 2 and 2 two related and important topics are described: the development of environmental indicators and technological change.

A documeny on Research Directions is inevitably incomplete. Additions to the current described research groups may be followed in the future by more detailed analysis. The research efforts and classification described in this document are complementary to the Scoping Report. A possible

matching of current research efforts described in this document with the possible entries of research described in the Scoping Report may provide some insights which elements currently have been underdeveloped. Such a matching may as well set the agenda for the development of IT towards a Science Plan which is aimed for presentation at the Industrial Transformation Global Conference, to be held in Amsterdam February 24-26, 1999.

3. 2. Macro Systems and Incentive Structure

Macro Systems and Incentive Structure:

Deals with energy and material flows through the economy and the eco-system and the process of societal change.

Includes:

1. Integrated assessment (climate change)
2. Industrial Metabolism (material and energy flows)
3. Material Flow Analysis (material flows from the perspective of regions)
4. Material Product Chain Analysis (material flows from the perspective of products)
5. Eco-restructuring (processes of societal change)
6. Ecological Economics (theoretical and empirical research)

Table 2: Macro Systems and Incentive Structure

3.1 Introduction

For the human dimensions programme of global environmental change, sub-part industrial transformation, a very important field of study deals with the physical exchanges between the economy and the ecosystem it is embedded in, and the various aspects that accompany these exchanges. The focus in this specific research field is often a system-analytic one, system-analytic because the human aspects that underlie such exchanges are supposed to be captured adequately by the system in which humans operate. That is, human behaviour, preferences and needs are often reduced to major homogenous groups with similar characteristics, such as enterprises, governments, consumers etc. The aim of this type of research is to describe how the interplay of these groups in society will influence pressures on the environment, identify broad categories of driving forces (such as technological change) without going deeply into the exact links between the various homogenous groups and their influence on environmental quality. The empirical oriented research in this area can differ, amongst others, along:

- Geographical scale (global, national, regional, cities)
- Objects of study (materials, emissions/wastes, products)
- Focus (flows or environmental effects)
- Temporal dimensions (including uncertainty)
- Spatial dimensions (distribution uniform or spatially diverse).

Typical research fields under the heading Macro Systems and Incentive Structure are those that deal with specific substances or environmental problems:

- integrated assessment (Section 2.2.) which is often dedicated towards modelling efforts and scenario building;
- more rigorous and theoretical research that deals with the extension of various disciplines in social sciences towards environmental problems, where the sub-discipline of ecological and environmental economics (Section 2.3) is relatively well-established.
- eco-restructuring, (Section 2.4) which deals with societal changes required to achieve a decoupling of economic growth and environmental impacts, for example through a factor 10 reduction in materials intensity of the economy; and
- mass balance related research which encompass industrial metabolism and material flow analysis (Section 2.5) which deals with a descriptive analysis of various materials and waste flows at the level of individual countries or regions.

In Section 2.6. some conclusions will be made on the system-analytical perspective in the research field of Industrial Transformation.

3.2 Integrated assessment

Integrated assessment in relation to climate change

Integrated assessment is a term that has frequently been used to describe the interaction between the economy and climate change. The standard view of integration refers to the causal chain that links human actions to its valued consequences. In assessment of climate change, this means assessment that considers the social and economic factors that drive emissions, the bio-chemical cycles and atmospheric

chemistry that determines the fate of emissions, the resultant effect of emissions on climate globa and locally, the impacts of climate change on managed and unmanaged ecosystems, and consequen on human activities and welfare, the actions undertaken to control emissions and thus effects and the social-economic aspects thereof. This view is commonly called "end-to-end" integration and reflects in this way the two-way impacts between global environmental change and society that is relevant for IHDP-IT.

Although integrated assessment can deal with a description of the current situation, most of the research efforts in this area are dedicated towards *scenario building* with the use of *models*.

These models then specify the frequently used *cost-benefit analysis* where the costs of responses are compared to the benefits of the impacts they mitigate. The research groups and efforts can be specified by the models that they have produced (see Box 1). Many of the problems encountered in the field of integrated assessment have already been recognised by the early efforts of the US Department of Energy (DoE) which established a program on Carbon Dioxide, Environment, and Society already in 1976. The working group on social and institutional responses in this program, for example,

Groups that are working on integrated assessment include the following

- Carnegie-Mellon University (developers of the Model ICAM);

- Massachusetts Institute of Technology (developers of a large integrated model, with associated activities);

- Battelle Pacific Northwest Laboratories--developers of the MiniCAM and PGCAM integrated assessment models and the State of the Art Report (SOAR) on social science and global change),

- RIVM, the Netherlands with models IMAGE and TARGETS (including health impacts and the first acknowledged "end to end" model

- University of East Anglia (ESCAPE model which extends IMAGE 1 0 to assess European policies and impacts)

- The Japan National Institute for Environmental Studies (AIM model to study the impacts of mitigation and adaptation scenarios on the Asian-Pacific region);

- Various policy optimisation models developed by f.e Electric Power Research Institute, USA, such as CETA and MERGE on f e adaption and abatement costs of greenhouse gasses The policy optimisation model DICE by Nordhaus (dynamic integrated models of climate change); The PAGE Model by Hope et al (a smaller integrated model that allows extensive specification and propagation of uncertainties), The CONNECTICUT Model--an integrated model that combines the approach of the DICE model with a probabilistic scenario analysis; the FUND Model by Richard Tol of the Institute of Environmental studies (a nine-region dynamic model that permits exploration of policies based on inter-regional financial transfers and damage compensation)

- Models developed at the Environmental Protection Agency (developers of the Atmospheric Stabilisation Framework (ASF), used to developed IPCC emissions scenarios, as well as the Policy Evaluation Framework (PEF) and the Adaptation Strategy Evaluator (ASE),

- The CSERGE Model--the Centre for Social and Economic Research into the Global Environment Model under development at the University College of London

Box 1: Research Groups in the area of Integrated Assessment

highlighted the importance of social scientists starting to study impacts and responses without waiting for atmospheric scientists to "finish" their work. The group recognised the need to start with partial equilibrium (equilibrium in one or a few economic sectors, without examining economy-wide effects) and comparative-static analysis, while slowly developing methods for general-equilibrium (equilibrium among all sectors of the economy) and dynamic analysis (studying changes over time) to permit consideration of progressively broader effects. They also recognised the central difficulty of selecting an appropriate level of disaggregation for the analysis, to provide an effective starting point for dialogue among different research disciplines and with the public and policy-makers.

In the 1990s modelling efforts have taken a huge flight, much of it inspired by the work of IPCC. Numerous fora and organisations have made significant contributions to the study of various aspects of global environmental change. Among them are the IPCC Working Groups, The Energy Modelling Forum at Stanford University (a forum for energy researchers to collaborate on the study of specific energy issues), The Global Change Institutes (an annual two-week intensive meeting of prominent researchers in global change and earth system science) and the recently initiated European Forum on Integrated Assessment.

Integrated assessment in relation to other environmental problems

There are numerous other examples of integrated assessment for other environmental problems. In general these are structured in the same way and with the same focus on forecasting as in the case of integrated assessment in the area of climate change. The report to the Club of Rome (Meadows et al , 1972, updated 1991) constitutes from many perspectives the starting point on integrated modelling of pollution, resource depletion and societal change. The DYNEX (or Stella) models that have been used for the forecasts have been heavily criticised for the deterministic approaches and the rather informal way various relationships have been modelled The impact of the Meadows report back in the 1970s was considerable: the combination of non-technical treatment of the issue and the dissemination through cheap paperbacks brought the topics raised by the authors under the attention of laymen and policy makers.

The Global 2000 (Barney, 1980) report to the President of the US was in the early 1980s another effort to integrate various economic and environmental models to provide a picture of future world pollution, resource and energy use. According to the authors, the integration was only partially successful and indeed the links between the various models seem to be poorly developed. Another integrated

modelling effort with high influence on policy makers has been the RAINS model on European Acid Rain, developed at the International Institute for Applied Systems Analysis (IIASA) beginning in 1983 (cf. Alcamo, Shaw, and Hordijk 1990). This project built on prior collection of emissions and deposition data, and development of transport modelling, that was conducted under the EMEP project (Co-operative Programme for Monitoring and Evaluation of the Long-Range Transmission of Air Pollutants in Europe) of the Convention on Long-Range Transboundary Air Pollution (LRTAP). Rains has a modular structure, including three major submodels for emissions, atmospheric transport and deposition, and effects. Emissions are based on externally specified population, economic, and energy growth paths, which can be varied between scenarios. A more firm integration of societal and environmental processes may be one of the steps ahead in the future of such integrative efforts.

The case of RAINS is important because of the strong link with policy making which can serve as a successful example of the use of applied scientific research results in the policy making process. The influence of RAINS has in part been attributed to a 1990 IIASA meeting where many heads of delegations negotiating on sulphur reduction targets interacted intensively with model developers over several days, requesting runs, specifying scenarios, and testing assumptions. The RAINS analyses have been credited with helping to persuade negotiators to move to non-uniform national emission reductions in the second sulphur protocol, signed in 1994. Once negotiators agreed to reduce divergence between deposition and critical loads by 60 percent over time whilst RAINS calculated cost-minimising national emissions to reach this goal, about half the delegations made the resulting number their final offer while several others took the emissions level but delayed the date by five to 10 years. RAINS has been extended to also account for the emissions of NOx and VOC. The deposition model from RAINS has been transformed into the TRACE model to estimate transport and deposition of heavy metals (cf. Olendrzynski et al., 1995) in the IIASA Regional Material Balance Project (see Section 2.5).

Many other regional projects on integrated assessment exists, that are often, however, very much oriented towards land use changes. One that can be mentioned is the project at the University of Maryland where the Institute for Ecological Economics works together with the Chesapeake Biological Lab. This project, which started in 1995 and will end in 1998 is aimed at developing integrated knowledge and new tools to enhance predictive understanding of watershed ecosystems (including processes and mechanisms that govern the interconnected dynamics of water, nutrients, toxins, and biotic components) and their linkage to human factors affecting water and watersheds.

Relevance of integrated assessment for IT and research gaps

Although land use problems are a key feature of many of the above mentioned models for integrated assessment, they also consider industrial activities as a source of emissions and are hence relevant for IHDP-IT too for two distinct reasons. First, an IT-program could contribute to integrated assessment efforts by better specifying the interactions between various groups in society in combination with production and consumption. Hence, IT-efforts could be complementary to existing research efforts. Second, one of the lessons that could be drawn from these modelling efforts refers to the problems that have arisen in the integration of social sciences with natural sciences. These problems are in general on the foot of social scientists, because it has proven to be extremely difficult to model social change if:

- technological change is still a poorly understood phenomenon;
- it is not clear to what extent costs born in the future should be discounted and at which rate;
- the influence of political processes and negotiations is hard to estimate;
- to what extent the valuation of socio-economic impacts can be established (losses in welfare, well-being, see also Section Annex 3)

Because of these 'unknown' facts, the process of integration of economy and ecology in integrated assessment differs widely between the various models. Besides that there is a considerable variety in how uncertainty has been dealt with in these models1, in the extend to which the analysis is disaggregated into sectors, regions, actors etc.2, and in the question whether the integrated assessment model is combined with other related environmental problems (which has only been done in the TARGETS model).

3.3 Integration between economics and ecology

Besides the models that are being used in scenario analysis, as being described above, there have been various efforts to integrate social sciences with ecological sciences. The integration of social with

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1 Tol (1996) argues that treatment of uncertainty is highly influenced by the software programs that allow an easy treatment of uncertainty.

2This can be mentioned a central issue in the system-analytical approach. A high level of disaggregation comes to the loss of insight in underlying relationships, whereas a low level of disaggregation makes the analysis unrealistic.

ecological sciences is perhaps most forceful in the field of *ecological economics*. Through the International Society of Ecological Economics, this serves as a much broader forum than solely the interplay between ecologists and economists, with additions from geographers and sociologists as well. They have a journal, biannual international meetings and regional branches with their own scheduled meetings.

Description of theoretical and empirical efforts

Theoretical research on the unwanted side-effects of pollution has in economics a long tradition, with the focus on policy prescription how such externalities could be internalized (Pigou argued for taxes, Coase argued for establishing markets through the allocation of property rights, Dales introduced the concept of tradeable permits). The allocative efficiency of taxes over rigid standards and subsidies has been proven in the early 1970s (Baumol and Oates). Recently more emphasis has been on the alteration of prices via financial and fiscal policies, such as accelerated depreciation, tax allowances and soft loans.

The micro-economic analysis on allocative efficiency of various policy interventions are in more recent years accompanied by investigations on the interaction between the economy and the environment from the macro-perspective. From an analytical perspective environmental impact models and macro-economic models have much in common, since both describe flows through the ecosystems (physical flows) and the economy (monetary flows) respectively. Linkage however, is hampered by the specific translation from the physical to the monetary flows (see De Bruyn and Anderberg background paper). There exists a wide variety of theoretical perspectives from which economic-environmental interactions can be described formally. Theories differ in general in their assumptions (for example on human and eco-system behaviour), analytical approaches (types of arguments: i.e. mathematical or contemplative - formalisation), time-frameworks (static or dynamic) or purposes (descriptive or predictive). An extensive and comprehensive overview has been provided by Van den Bergh [1996, ch2] who distinguishes 12 different analytical perspectives in ecological economics.

Theoretical improvements have taken place in the fields of:

1. **Physical aspects:**

- the incorporation of a dynamic concept of eco-systems carrying capacity (Tahvonen);

- the incorporation of the first and second law of thermodynamics (Ayres and Kneese, 1969; Georgescu-Roegen, 1971)

2. **Technology:**

- endogenous technological change (Starting from Becker, formalised in economics by Lucas and Romer with applications into environmental economics in e.g. Bovenberg and Smulders, 1995 and Hofkes, 1996).
- incentives to innovation (Perrings, 1989)
- sustainable technology (Perrings, 1994, Perrings and Pearce, 1994)
- the incorporation of evolution in economic or environmental processes or both (co-evolution), cf Gowdy (1994), Faber/Proops (1990).

3. **Institutional aspects:**

- the orientation on various aspects of government-failure (in the Public-Choice literature)
- joint implementation (the Berlin mandate of CoP1 of UNFCCC proposes the pilot project Activities Implemented Jointly (AIJ)).
- instruments of environmental policies (the OECD Council adopted a recommendation on the use of economic instruments in environmental policy (OECD, 1991)).

These improvements in the theories of economy-environment interactions are not fully integrated with each other at the moment. The various relationships between environmental impacts and economic activities can therefore not be fully determined from this type of analysis, but the theoretical contributions have pointed at many issues that are relevant, among these are: ecosystems behaviour, accumulation of pollution, education and knowledge, optimal investment strategies, availability of information to the government, double dividend arguments (labour tax reductions by raising environmental taxes), international trade and migration of dirty industries Research groups in this area are hard to define, since there are few established research groups, most of the work is done by individuals at universities.

Since the exact linkage between economic activities and environmental impacts cannot be determined from theoretical contributions, the empirical work in the field of material and energy consumption/production and emissions over time has been growing. The focus of the studies has gradually shifted from resource scarcity (raw material and energy availability) towards environmental scarcity (limits to environmental carrying capacity). One of the positions that has been put forward is that during the process of industrialisation, materials and energy consumption as well as emissions and

ambient air concentrations, may follow an inverted-U curve with respect to income (first rising levels of substance flows per unit of income but after a certain income level, falling levels of substance flows, first relative to income, later in absolute terms). For pollution, this has recently been called the 'Environmental Kuznets Curve' (Selden and Song, 1994). Evidence for such patterns have been found on a case-study basis for several materials and pollutants, as well as for energy, but almost solely for developed economies. The reasons given for such patterns given are quite diverse, and different research groups emphasize different elements but more efforts may be undertaken to fully understand the driving forces behind the observed 'inverted-U curve'.

Relevance of the theoretical and empirical efforts in ecological economics for IT

The theoretical and empirical efforts differ widely in scope and aims. For IT the theoretical research efforts are important for the insights that they provide on more broad categories of societal change and environmental impacts. Environmental considerations coupled with other societal aspects and eventual trade-offs between for example income and environmental quality can be made visible. The empirical work provides some insight in the patterns of environmental pressure along various stages of industrial development. Nevertheless many open questions remain to be answered. Some of the points that may be of relevance for a future agenda of IT in this field include the following questions:

Main research institutes that deal with empirical issues of economy-environment interaction include: Resources for the Future; Worldbank; Forschungsstellung für Umweltpolitik (FFU), Berlin; Vrije Universiteit Amsterdam (VUA); Rockefeller Institute (RI), New York; Bureau of Mines (BoM). Environmentally Compatible Energy Strategies Group at IIASA; SPRU, United Kingdom; CSERGE, United Kingdom. For energy especially much work is being conducted in South-east Asia, cf. National University of Singapore, South-Korea.

Box 2: Research groups working at empirical aspects of economy-environment interactions.

- Whether the current methodological pluralism is an advantage for the field. There is no common opinion: whereas some stress the fact that pluralism fosters the societal debates on the topic (f.e. Norgaard), others plea for common principles in order to make results and analyses comparable (cf. van den Bergh, 1996).
- Whether in this area of research normative principles should be chosen. It has been argued that the total level of 'throughput' (energy and materials) in the economy has to be limited (the steady state concept according to Daly) or to be brought into line with nature's carrying capacities by using the

concept of "environmental utilisation space".3 The environmental utilisation space is a powerful concept to highlight the limits of (material) growth, but it is hampered by definitional questions and empirical applications are sparse. Others have more ad-hoc argued for a reduction of the material intensity by a factor 10 or a factor 4 (Wuppertal Institute, Germany, OCW, the Netherlands). More fundamental and applied research on the justification and definition of such reduction targets could be of relevance for IT.

- The deterministic 'inverted-U curve' has always been strongly debated for it's lack of explanation and, recently, an international group of economists and ecologists in Science [Arrow et al., 1995] have pointed at the fact that this Environmental Kuznets Curve does not take into account ecosystems complexities with respect to carrying capacity and ecosystem resilience. In fact, they argue that empirical applications should be closer linked to the theoretical frameworks that have been developed in the field. A related problem related is that the theoretical contributions often use homogenous production (or substance flows), whereas the empirical contributions have not yet developed a common one-dimensional indicator for substance flows (see also Annex 3).

3.4 Eco-restructuring

Other full integrative efforts between economics and ecological sciences have emerged in the new research field of eco-restructuring. A drastic reduction of the material and energy flows due to human activities is the core element in the field of eco-restructuring. It is based on four principles (Erkman, 1994):

1- Reconsidering wastes as (potential) resources

2- Closing material cycles and minimise dissipative uses

3- A drastic dematerialisation of the total material throughput

4- Decarbonisation of energy flows

Whereas the first two principles deserve already attention in the literature on industrial ecology and are therefore being dealt with in Section 3, research in the latter two areas has both been studied in the area of sustainable consumption (Section 5) but also in the system-analytical research field through

3 "environmental utilization space" or "ecospace", is defined by Opschoor (1995: 127) as "the locus of all feasible combinations of environmental services that represent steady states in terms of relevant environmental

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Description of Mass Balance related research

Material flow analysis (MFA) describes the flow of a specific material through the extraction, use and dissipative uses in a specific geographical area. Since mass in equals mass out by definition, the tool of input-output analysis, developed in economics by Leontieff, has proven to be useful in combination with studies of material flows. The rows and columns in such an input-output analysis can be economic sectors or environmental compartments, and the matrix describes the exchanges between these. Hence, the MFA is purely descriptive and mostly empirical.

Adriaanse et al. (1997) develop a parallel set of physical accounts to describe economic activity and propose a new summary measure, the Total Material Requirement (TMR) of an industrial economy. The TMR measures the total use of natural resources that national economic activity requires and takes into account both hidden flows and foreign components of natural resource use as well as direct inputs of natural resources into the economy.

In connection with the MFA and also with LCA studies, analyses of the National Input/Output Table, particular of its Materials Tables, are being carried out by several Japanese economists and other researchers to understand the environmental loading of an industrial sector and its propagation to other sectors (see e.g Yoshinori et al, 1996).

Industrial metabolism is a closely related concept to the analyses described above, which attempts to pay more attention to the combination of various material flows together. Ayres (1997) argues that industrial metabolism is more "holistic" in the sense that the entire range of interactions between energy, materials and the environmental are considered together: consequently, traditional environmental regulation by medium may be far optimal as they result in shifts from one medium to the other (abated air and water pollutants that show up as waste) or shifts from one region to the other (through international trade for example). The concept of industrial metabolism may be closer linked to physical-chemical processes that combines various materials together under the addition of energy. It may also be closer linked to concepts found in the Industrial Ecology literature since some of the descriptive efforts that have been done at INSEAD (Ayres) have been devoted to the description of individual production processes.

Studies at different levels of geographical scale see: Industrial Metabolism in city regions: Newcombe et al.,1978 for Hongkong; Davidson et al., 1978 for Washington., van Dam et al., 1986 for Lelystad. Industrial Metabolism for river basins: Ayres & Rod, 1986, for Hudson-Raritan Basin; Brunner et al., 1994, for the Bünz Valley (Switzerland); Stigliani & Anderberg, 1994, for the Rhine Basin. Industrial metabolism in nations e g. van Vliet & Feenstra, 1982; Annema et al., 1995; Tukker et al., 1994 (Netherlands); Lohm et al 1994 .(Sweden); Schütz & Bringezu, 1993 (Germany) (There are also numerous efforts of materials accounting in direct connection with the statistical offices in e.g. the Netherlands, Germany, Sweden and France.). Mass balance analysis of EU-countries e.g. Rauhut, 1978; Akkermans et al., 1989; van Egmond, 1990. (There is also a whole flora of more general assessments of element and product flows Wuppertal and INSEAD and the life-cycle assessment litterature in Leiden). Some work on specific substances include: 1Heavy metals: Van der Voet et al., 1994; Gilbert and Feenstra, 1992; Anderberg et al., 1989; Stigliani and Anderberg, 1994, Chemicals: bromium: Prince, 1989; chlorium: Yanowitz, 1989; nitrogen: Norberg-Bohm, 1989a, sulphur: Norberg-Bohm 1989b, organo-chlorine compounds: Tukker et al 1994. IO-tables in the Dutch economy on materials and energy: Konijn and van de Boer 1993

Box 3: Scientific efforts in the field of Mass Balance Research.

Another concept that is relevant in this aspect deals with Material-Product-Chain Analysis (MPCA) which links both concepts form MFA and LCAs (to be described in Section 3.5.). MPCAs basically describe the material flows through the economy from cradle to grave of a specific products, such as automobile tires.

There have been numerous empirical efforts to describe the material flows at different geographical scales, with emphasis on different objects of study (see Box 3). One is particularly interested in a certain form of emissions (diffuse emissions, solid waste, atmospheric emissions) or environmental effects (soils, water) or in improving the efficiency of the overall flow. The diversity in this field is hardly surprising since the researchers in this field have varying disciplinary backgrounds and start off with different questions and basic knowledge. Most researchers are probably economists, biologists, chemists and chemical or civil engineers.

Most studies try to reconstruct the mass-flow in a region (system) during one particular year, but there are also studies with a long or very long historical perspective (e.g. the Hudson-Raritan Study, the Swedish project on Accumulated Environmental Impacts and the Rhine Basin Study). The studies are in general descriptive and can be described as inventories: they strive at organizing data to draw conclusions that can be relevant to materials management policy. There are also examples of studies which perform an analysis of alternative future development trends This is most common when a construction of a computer-based model is central in the study (e.g. Virtanen & Nilsson 1993 (Paper recycling in Western Europe))

Various communication channels exist in this area of research. Especially the recent established network of Connaccount attempts to present a communication channel through which results of European MFA and IM studies can be dispersed. Detailed overviews of various research groups are available from Conaccount (see Annex 1).

Policy implications

Material Flow Analysis and Industrial Metabolism have been perceived and presented as an important tool of analysis in an integrative approach that is able to improve study methods, as well as our ability to develop sustainable strategies. The implications of this perspective are the following: to change and decrease the inflows and to improve efficiency and recycling. These implications have been summarized in the goal of "closing the loops" and have been widely accepted in environmental politics. For example, in Sweden, "flow thinking" has become a fundamental part of the environmental policy. The breakthrough of the flow perspective is probably due to the growing dissatisfaction with conventional strategies for environmental protection; these strategies have not been completely successful in solving environmental problems, such as to deal with the growing "waste mountain" or how to decrease diffuse consumer-related emissions. In addition, the flow model communicates very well with the natural and ecological sciences.

Relevance of mass balance oriented research for IT and research gaps

Currently few efforts discuss difficulties, uncertainties, and constraints of the MFA and IM studies. The difficulties encountered in these studies are rather obvious. First, statistics do not adapt very well to this type of study and the information on different types of emissions is limited, relatively uncertain and hard to generalize. Besides, the performed studies are also severely limited.their ability to evaluate the social development and to create a basis for analyzing development strategies and policies. It is e.g. difficult to connect the flow analysis of single elements, such as heavy metals, to wider issues that have a far-reaching effect on the environment: spatial and temporal aspects, economic and technological change, and decision making in politics, administration and industry. Material substitution is a neglected aspect of the studies. Besides, several studies have taken a static perspective, by only looking at data for one year. The flow analysis communicates well with environmental impact analysis, but its linkage to a wider analysis of society is more problematic. This is particularly true when little attention is paid to societal development, enterprises and industries, and institutional frameworks, and when the choices of region and study object are based on natural scientific considerations.

These problems indicate that there is scope for an IT-program that can enhance the understanding of, and encourage the linkage with societal phenomena in the area of mass balance research.

3.6 Macro Systems and Incentive Structure: conclusion

In this description of Macro Systems and Incentive Structure related to Industrial Transformation a variety of research approaches has been discussed. Common theme in this perspective deals with the interaction between the environment and the economy from a wide variety of perspectives (in terms of environmental problems, in terms of description of societal processes and in terms of paradigms).

The various research perspectives in the field of Macro Systems and Incentive Structure may come together in the following research framework. With the insights from the research areas of integrated assessment, industrial metabolism and material flow analysis the pathways of carbon and various materials through the economy and the eco-system are being described empirically. The interactions between these pathways and the underlying structuring of society are being dealt with in the areas of environmental and ecological economics. In these areas of research, also prescriptive norms are proposed, such as a reduction of Factor 10 in materials intensity. Eco-restructuring deals with how such goals can be attained.

This broad research area forms a subject that lends itself for research with the central question how economic activities can be decoupled from their environmental impacts, with the possibility of defining specific decoupling percentages. Areas of research that, in addition, may be relevant here deal with investigations into economic transformation processes, such as the restructuring that took place in relatively old industrial areas such as Pittsburgh or the Ruhr area. These research efforts, in regional economics and sociology, may have relevance for a historical investigation in transformation processes accompanied in processes relevant to the social community.

So far the discussion on the top-down, system-analytical part of IT research. The next section continues with the firm level perspective, starting with the area of *industrial ecology*.

4. 3. Industrial ecology: From eco-efficiency to sustainability

Pollution Prevention (P2)	equipment modernisation, maintenance and operation practices improvements, inventory control, input substitution, in-process recycling P2 applies primarily to existing plants and operations.
Cleaner Technology (CT)	development of new technologies that replace existing polluting technologies.
Life-Cycle-Design (LCD)	includes environmental considerations in the regular design process of products and production processes.
Closing the Loop	recycling, remanufacturing, industrial ecosystems, product stewardship, design for disassembly, reverse logistics.

Table 3: organisational framework for eco-efficiency

4.1 Introduction

Industrial ecology (IE) systematically analyses the interactions between industrial activities and the environment (Ayres, 1989; Ayres & Simonis, 1994; Frosch, 1995; Frosch & Gallapoulos, 1989; Greadel, 1994; Greadel & Allenby, 1995). IE requires a systems view as it is concerned with the environmental impact and dependencies of the interrelationships, interactions and interdependencies within communities of businesses and ecosystems of communities (Raymond Coté, personal communication, November 1997). It focuses on "connections between the natural world and technological society" (Lifset, 1997), and thus allows the researcher to address pertinent issues related to sustainable development:

- the functioning and limits of sources and sinks in the biosphere that provide resources and services for human society (discussed in the preceding chapter),
- the cycling of resources in nature as a profitable source of insight in, or even a model for, industrial activities (the focus of this chapter); and,
- questions of how the organisation of industry, the structuring of markets and the behaviour of firms affect the quality of the natural environment (to be discussed in the next chapter).

The recognition of the 'biological analogy' or the 'ecological metaphor' by Ayres in 1989 was an important conceptual step forwards It implied the opportunity, yet far from fully explored, of expanding firm, plant and site-specific measures for pollution control, such as end-of-pipe technologies,

best-available technology and pollution prevention, across firms in industrial sectors to production chains and networks (*filières*) and linking them to the more encompassing objective of sustainable development. The German concept of the closed-loop economy, the *Kreislaufwirtschaft*, is a logical corollary of such thinking.

However, when considering the activities of firms and industries presented under the heading of industrial ecology, it is to be acknowledged that most attention is at increasing the efficiency of resource use, closing materials cycles, dematerialisation by relying on inherently more benign substances and production methods, and at the reduction of pollution over the entire life-cycle of products and services. The objective is to avoid the shifting of pollution from one environmental compartment to another, from one pollutant to another, from one place to another, and from the present to future generations. The focus is more at eco-efficiency than at sustainable development. Thus, in spite of the relative underdevelopment of the more rigorous research field of IE, the ecological efficiency of industrial production has become the focus of a growing range of innovative and promising research activities which can be summarised under the heading of *eco-efficiency* (see Hertwich 1997 for elaboration) Several strategies for enhancing eco-efficiency can be distinguished:

- pollution prevention, cleaner production and clean technology (focusing on reducing pollution from existing plants and processes);
- eco-design, life-cycle-design (LCD) (focusing on the inclusion of environmental considerations in the regular design of products and production processes); and
- closing the loop (focusing on re-use and recycling of waste-products).

These strategies differ with respect to the different stages in manufacturing such as the regular design of processes and products, the operation and maintenance of existing plants, or the development of new technology Of these strategies pollution prevention, life cycle design, and closing the loop have gained most attention in the industrial ecology literature and will be dealt with in separate sections below. Issues of environmental management will be dealt with in Chapter 4. A common and recurring theme when considering literature and research in these fields is that 'eco-efficiency' is not enough. Rather than doing 'more with less', and attitude of 'enough with less' (Van Weenen, keynote speech at 3rd European Round Table on Cleaner production, 1996) is required. The implications of such a shift are only barely being discovered today.

Industrial ecology (IE) is a young research area where professional societies are emerging. Dedicat conferences are still lacking but at various other conferences topics of interest to IE are regularly bei discussed. Important conferences include: the Greening of Industry Network Conferences (Ron November 1997), the European Round Table of Cleaner Production (Lisbon, Summer 1997), and t Business and Environment conference (Leeds, September 1997). An important step to establishing IE a community of researchers and as a research area has been the launch of the *Journal of Industr Ecology* in Spring, 1997. Other important journals include *Business Strategy and the Environme* UNEP's *Industry and Environment*, the *International Journal for Environmentally Conscious Desi and Manufacturing*, the *Journal on Cleaner Production*, the *Pollution Prevention Review* and standa engineering journals. Important platforms for exchange among eco-design experts are the ann meetings of the CIRP and the annual IEEE Symposium on Electronics and Environment. Many of (university-related) institutes working on life cycle design issues have developed websites. A listing more than 80 links on "eco-design and cleaner production" may be found http://www.sms.utwente.nl/vakgr/br/links.htm. Another website provides a listing of journals newsletter devoted to cleaner production, pollution prevention, green design, business and environment, etc. on http://www.igc.apc.org/eco-ops/EQE/Periodicals/welcome.html.

Important centres of eco-design, pollution prevention and cleaner production include the R Melbourne Institute of Technology in Melbourne, Australia (director Chris Ryan), the Centre Sustainable Design at the Surrey Institute of Art & Design in the UK (director Martin Charter), Delft University faculty of Industrial Design in the Netherlands (director Han Brezet), the Center Clean Products and Clean Technologies at the University of Tennessee (director Gary Davis), University of Windsor, in Canada (Andrew Spice), the Erasmus Center of Environmental Studie Rotterdam (Leo Baas), the UNEP Woking Group on Sustainable Product Development, based at University of Amsterdam (director Hans van Weenen), the ICPIC database on cleaner produc maintained by UNEP in Paris, the University of Michigan School of Natural Resources (Greg Keoli and ENSAM in Chambery, France (director Rémy Blancon).

4.2 From Pollution Prevention to Sustainable Production

Pollution prevention (P2) focuses on process optimisation, input substitution and better housekeeping measures. P2 is closely related to cleaner production activities and the development of clean technologies. The US Federal Pollution Prevention Act of 1990 specifically lists seven source reduction practices:

- equipment modernisation and modification,
- improved maintenance,
- improved operation practices,
- inventory control,
- process and/or product modification,
- substitution of inputs, and
- in-process recycling.

In the US, P2 is highly developed. Local, state and federal pollution prevention officers, industry representatives, consultants, and NGOs have created the National Pollution Prevention Roundtable (NPPR) as a forum for exchanging P2 experiences and as a means to coordinate the activities of P2 offices and programs. NPPR working groups deal with facility planning, technology research, technology transfer and regulatory integration. NPPR also provides a directory of P2 offices and programs and lists their focus as well as their experience. The American Institute for Pollution Prevention (AIPP) and the National Pollution Prevention Center for Higher Education (NPPC), on the other hand, designs teaching material (Ross, 1992) and technical guides, e.g., on financial analysis of P2 projects (AIPP, 1993). They are publishing checklists and case studies and offers grants for developing pollution prevention programs. In Europe, the EU program PREPARE promotes pollution prevention and finances supporting research. Local initiatives such as Ecoprofit in Graz (Austria) are now part of PREPARE. The Zero Emissions Research Initiative, connected with the United Nations University in Tokyo, forms a forum where a number of global corporations are exploring the possibility of a zero waste company (Molloy & Ueki, 1997; website at http://www.zeri.org).

Freeman et al. (1992) provide a comprehensive review of pollution prevention, including international and US federal, state, local and corporate efforts. Geiser and Crul (1996) provide a good overview over pollution prevention in small and medium size firms. Freeman and colleagues at the US EPA's Pollution

Prevention Research Branch in Cincinnati (Ohio) and Pacific Northwest Pollution Prevention Rese Center in Seattle (Washington) are a major source of the hundreds of case studies that have published in recent years. An international compendium of industrial pollution prevention published by the EPA in 1994. The large set of resources available to the practitioner has recently summarised in two handbooks (Freeman, 1995; Higgins, 1995).

Pollution prevention is an important area of IT where engineers, managers and scientists mee integrative and applied efforts to minimise the environmental impacts from production, use/opera and end-of-life management. Issues that have not yet been satisfactorily been answered inc questions of why many apparently obvious and profitable opportunities for source reduction, en conservation, etc. are not being explored by companies.

Many criticise P2 as being too much focussed on 'in-house' measures. To them, P2 is further evol into 'cleaner production' by which a more comprehensive preventive approach to environme protection is meant, one that addresses all phases of the production process and product life c (Kirsten Oldenburg in *Journal on Cleaner Production*, no reference available) or even to 'sustai production' if one moves beyond the environmental optimisation of production (Van Weenen, key speech at 3rd European Round Table on Cleaner production, 1996).

4.3 From Eco-design to Sustainable Product Development

The idea to address environmental questions at the design stage derives from the observation th least 70% of the decisions concerning pollution in the subsequent manufacturing, use and dis stages are made during the design of a product (Sheng et al., 1995). Life-cycle engineering, design and manufacturing, design for the environment and eco-design are some of the many name LCD, their number and diversity reflects the multiple origins of an idea developed in parallel by different researchers and engineers. LCD is very knowledge intensive, it requires a good understa of the manufacturing process and—depending on the scope and ambition of the effort—of the us end-of-life stages of a product, as well as a way to assess and compare different kinds of environm impacts.

LCD can be disentangled in various research efforts. Many North American research groups focus on the environmental optimisation of single components or manufacturing processes. The dominant European approach—life-cycle engineering—aims to consider a product's environmental impact from cradle to grave Alting's research group, the Life Cycle Center at the Technical University of Denmark, has been instrumental in applying life-cycle assessment (LCA, see Section 3.6.) to product development (Alting and Jorgensen, 1993; Alting and Legarth, 1995). To date, life-cycle engineering can address only simple features or products such as vacuum cleaner tubes (Weule, 1993; Zürn and Diener, 1994), fastening devices (Shu, et. al. 1996), or materials selection in automobiles (Young and Vanderburg, 1993). A consortium of European electronic companies, however, is in the process of conducting an LCA of a generic television set under the umbrella of EUREKA. The third strand of LCD relies less on complex models of manufacturing processes or extensive investigations of product life-cycles but develops general design rules that may result in practical improvements of the environmental performance of products and relies on various matrix approaches to identify crucial pollutants and processes (Graedel et al., 1995; SRRP, 1993; Veroutis and Fava, 1996). Graedel et al (1995) have applied their matrix approach to generic automobiles of the 1950s and 1990s and have identified energy use and gaseous emissions as the worst problems in the 1950s and materials choice in product use in the 1990s

DFE is mostly conducted by engineers. However, there seems a role for social sciences since the adoption of DFE depends on the development and testing of tools that can be used by the designer to design, identify, and/or select environmentally friendly features. Current work indicates that researchers have different ideas about how they can provide designers with the necessary information and the incentives to pursue DFE. Solutions will differ according to industry and corporate culture (Ehrenfeld 1997).

The general critique on DFE as focusing on incremental improvements of products is increasingly being addressed Van Weenen (1997) argues that 'sustainable product development' is needed, and that it provides opportunities for, and benefit from, knowledge, experience and renewable materials from the South. It requires, however, a better understanding of the design process and designers' decision frame as well as insight in the position and role of the designer in the overall innovation process Recent work by Ph.D. students from Delft University are promising starts in this direction; it should result in challenging the currently dominant eco-efficiency approach in eco-design by making designers question the functionality of a product from a system's perspective (Kruijsen, 1997; Van den Hoed, 1997) For example, when designers start addressing consumers' needs—transportation—rather than developing

specific products—a car—new solutions with significantly improved environmental performance at systems level may emerge—car sharing— (Meijkamp, 1997).

4.4 From Isolation to Collaboration: Closing the loop

The proponents of industrial ecology propose to reduce emissions and resource use through a reduc of dissipative materials use, especially through a cycling of materials inside the industrial system and increase of materials efficiency. The idea of closed material loops is at the core of the IE concept. Andrews et al. (1994) assert: "The natural ecosystem analogy suggests that almost total recycling materials would be a key feature of a future industrial ecosystem" (p.473).

The ecosystems analogy provides strong links to the industrial metabolism literature (Section 2.5), bu has also been developed and implemented at the local level. When several firms within a close dista exchange 'waste flows' as secondary raw materials, as well as energy in different forms (stream, he they have developed a local industrial ecosystem or an eco-industrial park. The Danish town Kalundborg hosts the much cited example of such an "industrial symbiosis": waste streams and ene are exchanged between a 1500 MW coal-fired power station, an oil refinery, a gypsum plant pharmaceutical company, farmers and fish ponds.

In spite of the fact that the paradigmatic example of eco-industrial parks (Kalundborg) is located Europe, the most encompassing approaches in this field seem to be developed in North America. T School of Resource and Environmental Studies at Dalhousie University in Halifax (NS), Cana (director Ray Coté) and the Work and Environment Initiative at Cornell University (director Ed Coh Rosenthal) are leading centers where the concept of eco-industrial parks is further developed. The EPA sponsors the design of waste exchanges and the planning of the co-siting of industry, e.g Brownsville, Texas. Bechtel Engineering is currently developing tools for the creation of eco-industr parks (Cobb, 1996). In addition, a field book for the development of eco-industrial parks and a resou guide will be made available by EPA (Lowe et al., 1996; Lowe and Warren, 1996). In many ot countries including China, Germany, Indonesia, Mexico, the Netherlands, Peru, Thailand, and Tunis experiences with eco-industrial parks have already started. An interesting example is to be found in Philippines where the IWEP project (Industrial Waste Exchange - Philippines, started in 1988) resulted in an information data base where firms can trade their waste products. In a publication some 600 waste residuals are published that can be traded.

Whereas much work on eco-industrial parks has quickly been taken up by practice-oriented research institutes and consultancies, questions remain on the effectivity and efficiency as well as on organisational and innovation aspects. For example, O'Rourke et al. (1996) point out that industrial ecosystems such as the one developed in Kalundborg, require stable contractual relationships among the companies that participate in the "ecosystem" so that each company is guaranteed the material feedstock it requires. This reduces firm flexibility and may lock in certain technologies. Gertler and Ehrenfeld (1996) provided a good overview of how the Kalundborg waste cascading system has developed over time; they appropriately acknowledge the importance of local culture and stringent environmental regulations for the evolution of industrial waste exchange.

Closing the loop has also been promoted along the production chain, especially in relation to emerging 'extended producer responsibility' and the various 'take back and recycling' regulations being implemented in Europe and abroad. Industries affected by such regulations include the packaging, automotive, and consumer electronics industries, and other industries are expected to follow Interesting examples from several large Japanese firms in the image and information processing industries on closed-loop recycling are collected in Baba et al. (1997). An important conceptual predecessor to the 'life cycle management' of products is the acknowledgement that companies may achieve improved environmental performance by cooperating with suppliers (various contributions in Fischer and Schot and Fischer, 1993). Based on experiences with life-cycle management in the Netherlands, Cramer (1996) and Cramer and Quakernaat (1994) propose a methodology that starts with analysing sources of environmental impacts of a product during all the stages of its life cycle.

4.5 Tools: Life Cycle Analysis

Life cycle assessment or analysis (LCA) is an important tool for eco-efficiency. The aim of LCA is to provide information about environmental impacts in production, use, and disposal of different products. The development of LCA was prompted by the desire to avoid shifting pollution to different life cycle stages when minimising pollution at the specific stage. In DFE it helps designers to select materials and decide about product features. For clean technology and environmental management systems, LCA serves to identify the life cycle stage with the largest environmental impact. Hundreds of consultants and researchers are involved in developing and applying life cycle assessment (see Box). LCA has been formalised by the Society of Environmental Toxicologists And Chemists (SETAC) and consists of four

phases: goal definition, inventory analysis, impact assessment, and improvement assessment (Consoli al., 1993; Owens, 1997). LCA is very labour intensive because it requires the collection of process a emissions data from all life cycle stages. As a result, most LCAs have focused on simple products parts of products (packaging material, baby diapers, car components). Increasingly, standardi databases containing the life cycle data of input materials and standard processes are becoming avi able. Frequently, these databases are part of computer-based tools, e.g., for the selection of packag materials (Alting, 1995). With the accumulation and spread of this kind of knowledge, m complicated products can be investigated.

The most ambitious effort to date is the ongoing life cycle study of a generic television set by consortium of European electronics companies. Most LCAs stop at the inventory phase. Efforts standardise the impact assessment procedure are still underway and are hampered by the absence o common metric (see Annex 3).

Owens (1997) provides a critical review of the LCA methodology. He points out that impact assessm step in LCA is highly problematic because of the loss of spatial, temporal, dose-response, and treshi information in the inventory step. Therefore, he goes on, LCA does not measure actual effects impacts, nor does it calculate the likelihood of an effect or risk. Such problems may not be countered further standardisation of the methodology.

Different LCA methodologies have been developed, but hardly has a beginning been made with assessing their applicability in policy or by management. Van Drunen (1997) and Berkhout (1996) have assessed the role of LCA in decision making. While acknowledging the methodological issues mentioned before, they warn against too rigid standardisation of LCA. Different types of LCA are used as appropriate tools in specific situations; indeed, it is the potential versatility of the method that has led companies, government authorities, NGOs, etc. to having adopted LCA for informing specific decisions. They conclude that more research should be done on how potential users may benefit from LCA and on how the decision making context structures the potential use of LCA Schaltegger (1996) is more pessimistic on the applicability of LCA. He argues that LCAs are impractical decision tools for policy makers because the information cost for developing a detailed and generalised LCA are prohibitive. On the other hand, for companies completeness of data sets for their own step of LCA is not a problem, but extending LCA data sets for subsequent and previous steps poses problems of relevancy for decision making.

Prominent research centers on LCA include the Center for Environmental Science at Leiden University (Netherlands), the Laboratory for Energy Systems at ETH Zurich (Switzerland), the University of Sankt Gallen (Switzerland) the Center for Life Cycle Engineering at the Technical University of Denmark, Proctor and Gamble's research centre in the Netherlands, and Roy F Weston, Inc., the Pacific Northwest Laboratory and the National Pollution Prevention Center of the University of Michigan in the United States, Ecobilan (Paris, France), and the Wuppertal Institute in Germany. In the early days of LCA, BUWAL (Switzerland) contributed various important insights. In addition to SETAC, the International Standards Organization (ISO) and SPLOT provide important forums for the standardization of LCA. The new *International Journal of Life Cycle Assessment* and the *Journal of Cleaner Production* are important journals in the field.

Box 5: Research institutes on LCA

4.6 Relevance for IT: Towards broader policy frameworks?

Several different strategies for companies focusing on environmental aspects have been defined. They form the basis of research that one would label as Industrial Ecology. Further development of IE as a coherent framework of these strategies is required. Most of the research conducted under the heading of eco-efficiency is applied and relatively technical. When, in the future, this research will be more closely connected to the social sciences and policy analysis, three problems deserve scientific attention.

Market failure?

The first is related to the question why do profitable pollution prevention opportunities continue to exist in many companies, often for decades? Contrary to the assumption of neo-classical economics, companies often seem to be far from profit maximising and are reluctant to pursue environmental improvements even when engineering-economics calculations show those to be profitable. Empirical work on this has been conducted in the area of energy conservation potentials. The persistence of substantial opportunities to both reduce energy consumption and increase profits has led analysts to postulate the existence of an "energy-efficiency gap." Research into why residential, commercial, and industrial energy consumers do not take advantage of energy-efficiency investment opportunities has become a focus area in energy efficiency research and is driven in part by the frustration of policy makers. The efficiency gap has been explained in terms of high information costs, sensitivity to high investment costs and liquidity constraints, bounded rationality, and principal-agent problems. Energy efficiency researchers have yet to agree on an explanation or on the proper policy response (Golove, 1994; Jaffe and Stavins, 1994; Velthuysen, 1995; Golove and Eto, 1996).

Implementation of eco-efficiency?

A second related problem is that the design of an effective environmental policy crucially depends on a better understanding of when and to what degree companies will implement eco-efficiency. Research is needed into what makes industry moves, i.e. into the incentive structures. Eco-efficiency is driven by a combination of greening factors, including cost-reduction opportunities. In some cases, pro-active companies make a conscious strategic effort to improve the firm's environmental image and to avoid regulatory burdens and future liability. However, greening research currently has not succeeded in identifying the relative importance of the various greening factors and the (hierarchical) relationships

between them, nor has it made explicit which factors are manipulable, and which not (Fuchs and Mazmanian, 1997). Berkhout (1996) discusses drivers for the adoption of LCA and presents empirical research on the adoption of LCA in Europe. He concludes that market and regulatory pressure on industry currently do not provide clear signals encouraging companies to optimise product systems according to any environmental criteria. Consumer demand for clean products influences only the final goods producer, and there is insufficient consistency of interaction to propagate such demand through the supply chain. The interest of industry in life cycle assessment, and hence the ability of LCA to reduce environmental burdens, is limited to highly visible final goods producers and to basic industries that receive increased public or regulatory scrutiny.

Environmental impact?

The third problem is related to the overall environmental success that pollution prevention and related strategies can provide. Pollution prevention advocates have traditionally focused on success stories. These case studies help to stimulate the interest of industry, but they do not provide policy makers with insight in the potential role of each eco-efficiency strategy in environmental policy. Comprehensive critical overviews of P2 by EPA and OTA have discovered little evidence for a substantial pollution reduction (Ashford, 1993, p 291). A better understanding of how and how much eco-efficiency can reduce pollution is needed to develop policies that can support the implementation of the strategies. Assessing the effectiveness of eco-efficiency requires two elements: a model and understanding of firm decision making and the ability to assess and compare the overall pollution of industry. Efforts in both areas exist but need to be intensified. Such efforts can be made in a combination with organisational studies (Chapter 4) and the system-analytical approaches discussed in Chapter 2.

1. 4. Firms: Organisations Management and Networks

Organisations, management and network theories.
Research aimed at improving organisational design and understanding organisational behaviour from the perspectives of specific firms in combination with their wider socio-economic and environmental surroundings.
Contains:
1. Organisational behaviour and design (insights in the environmental performance of private and public organisations)
2. Environmental management (changes in management structure that increase corporate attention in environmental issues and document changes relevant to the environment)
3. Network theory (enhancement of linkages between public and private organisations that can improve environmental efficiency)

Table 4: Organisations, management and networks

1.1 Introduction

The Brundland Report considered organisational and technological change to be two primary means by which sustainable development by industry was reachable. Yet surprisingly little scientific effort has been devoted to the role that organisational research can play in 'the greening of industry' (see Working Paper IHDP-IT No. 5 by Welch). In one of the most recent overviews of the private sector environmental organisation literature, Gladwin (1993) concluded that ".. most of it (industrial greening literature) is merely descriptive, boiling down to journalistic storytelling and case studies." Alternatively, too little of it is driven by theory and rigorous methodology. As a consequence, greening is probably in an age of "superstition," in which economist F.A. Hayek defined as a 'time when people imagine that they know more than they do (Gladwin, 1993).'" Gladwin has summarised these and other shortcomings in a list of ten criticism about the state of the current scholarship on 'industrial greening': lack of a definition of environmental management (greening), lack of empirical findings, lack of cumulative knowledge or research, lack of interest in causality, lack of general rigor of research, lack of systematic comparative study, lack of dynamic empirical or theoretical design, lack of building and validating general models, distancing of research from advocacy, no attempt to place research in broader streams of organisational change literature.

The apparent marginalisation of the natural environment within organisation research has also received critical attention. Shrivastava used the graphic metaphor of "castration" to force notice of the extent to which organisations are often perceived in current research to be removed from the natural environment in which they act (Shrivastava, 1994). This gap has also been characterised as a "[separation] of humanity from nature..." in the strategic management literature (Gladwin, Kennelly and Krause, 1995). In fact, the physical environment has traditionally been treated as a constant in organisation research much as it has been treated as an externality in neo-classical economics.

Remarks of this kind indicate two gaps that need to be addressed by the industrial transformation program. The first concerns what appears to be a general lack of research and understanding about how organisations relate to their broader ecological environment. A potential struggle in the organisation studies field may exist between those who consider ecological issues to be an additional variable in the explanatory model and those who consider ecological sustainability to be of great enough importance that a more dramatic revision of existing theories need take place. The second relates to the insufficient application of existing theoretical and empirical findings about organisations to issues of environmentally sustainable industrial practice. Specific areas of potentially fruitful application would include the literatures of organisational theory, organisational design, organisational behaviour, and network analysis. These areas of application are described briefly below and in more depth in the IHDP-IT working paper by Welch.

Within the context of an environmental systems perspective of industrial transformation, all of these research areas hold promise. This may be especially true for network analysis in which inter-organisational linkages could provide significant new insight about how and why green policies are adopted by firms during processes of change. However, it is also of critical importance that traditionally non-systems oriented organisational analyses be conducted as a means of better understanding why and how sustainable policy and practice is adopted, rejected or altered at the organisation level.

1.2 Existing Resources and Research

Interdisciplinary social science programs that conduct research in these areas can be found at the Center of Clean technology and Environmental Policy at Twente University, Enschede, The Netherlands; the George Perkins Marsh Institute at Clark University in Massachusetts;

The Center for Environmental Policy and Administration at Syracuse University, New York; The School of Public and Environmental Affairs in Bloomington, Indiana; The Ivan Allen College of Management, Policy and International affairs at Georgia Institute of Technology; INSEAD near Paris, France; WIMM at the University of Amsterdam, the Netherlands; and Vanderbilt University in the US.

Only a few of the journals in organisation theory have actually devoted space to exploring issues of sustainability in organisations. These include *Strategic Management Journal*, *Management Science*, *Long Range Planning*, *International Journal of Industrial Organisation*, and *Academy of Management Review*. Other, more applied journals in this area include *Business Strategy and the Environment* and *Total Quality Environmental Management*, although both of these also publish some theoretical research.

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The issue of environmental management is to one of the elements discussed in the Greening of Industry network (although this network is broader and encompasses issues from industrial ecology and sustainable consumption). More applied journals in this area include *Business Strategy and the Environment* and *Total Quality Environmental Management.*

Network-theory in combination with environmental issues have been discussed in the journal of Environmental Politics.

Box 6: Research groups and journals in the area of organisation, management and network analysis.

Other important resources in the field include research groups, organisations and conferences. The major organisation in the field is the Greening of Industry Network, which also holds its own annual conference. Business Strategy and the Environment is the name of another annual conference held to present primarily applied research on the private sector environmental management trends and practices. Specific research groups relevant to these areas are hard to define and typically comprise networks of individuals from different campuses rather than dedicated research centers. Box 6 provides an overview of some of the active research groups and journals that can be distinguished in organisation research.

1.3 Four Aspects of Organisations with Relevance to Industrial Transformation

There are essentially four interactive components to organisation level research as it relates to industrial transformation. organisation attributes, the context within which firms operate, internal operational and management functions and decisions, and inter-organisational relationships and structure. The objectives of industrial transformation require significant understanding of the dynamics of all four in order to apply many of its precepts. The attempt here is to briefly describe these components and their interaction, provide examples of research relevant to IT, and suggest potential future areas of research.

Organisational Attributes

Firm attributes are typically considered to be a very straightforward categorisation of organisation level research One attribute that is often cited as an important factor for consideration is size Large and small firms are treated differently, or at least, there is empirical support that firm behaviour, structure, placement within a network system, life span, and other often cited traits vary with size. However, with respect to the greening of industry, Geiser and Crul argue that little research has been conducted on small and medium sized firms (Geiser and Crul, 213, 1995). Because much of what we do know often comes from best-practice research conducted on large firms, the argument for less

size discrimination in the greening research is appropriate. In addition to size, centralisation, formalisation, and hierarchy have been shown to be related to innovation capacity, environmental leadership, risk aversion, adaptability, and market and political power. This indicates that the internal structure of organisations is an important component in understanding how organisations can or would undertake activity for sustainable change.

Firm attributes are also important considerations for understanding the boundaries, boundary spanning behaviour, and the position and role of organisations within a complex network. The extent to which firm boundaries are changing in reaction to strategic desire or institutional necessity is of interest. Organisational greening activity that seems to carry with it requisite trust of communities and increased network linkages, may mean that organisations are becoming more integrated and less isolationist than was previously true. Such stipulation requires significant empirical analysis, but is none-the-less an interesting topic of analysis. Policy that advocates of such instruments as product stewardship and chain management need be aware that the success of implementation and impact probably varies with firm attributes. Outcomes of policy direction - in terms of competitiveness or viability of individual organisations - may create winners and losers. How such information is incorporated into policy choices is of primary concern to the success of industrial transformation policy. One way to develop equity corrections for environmental policy that biases economic outcomes is to identify winners and losers on the basis of selected attributes. Currently, it is not possible to conclude whether cultural changes are causing different environmental performances as a result of environmental management or other factors, such as comparably better management or organisational adaptability (Wehrmeyer and Parker, 1996).

The Context of Organisations

The second area of research interest - context - refers to the social, political, economic, geographic, legal and environmental setting in which a firm exists. The external context of an organisation constantly changes and the speed of that change varies creating a continuum that runs form stable to turbulent. Three ways in which organisations are seen to interact with their contextual environments include: organisations as change agents (such as the transformational leadership model); organisations as active adapters (models such as

strategic choice, dynamic resource allocation, or organisational learning); or organisations as embedded within the constantly changing context (institutionalisation or natural selection models). To give an example of how organisations interact with their setting, recent work by Wishart, Elan, and Robey shows that development of capacity for organisational learning is a highly complex task that is often "wildly experimental, intensely focused around team processes, and operating in a virtual time/space network..." They go on to say that "ongoing experimentation (with new activities), [continually] innovative human resource programs, radical revision in structure, and generous doses of [technological change] ... may simply be too risky [for many firms], especially where payoffs uncertain (Wishart, Elam, and Robey, 1996). The parallel between the existence of issues of Greening and energy saving behaviour of companies is waiting to be exploited. In various studies the energy-efficiency gap in relation to company attributes has been addressed.

Each theoretical perspective provides a potentially important contribution to understanding how industrial transformation can take place. Moreover, assuming each perspective carries some validity, each allows application of different notions of industrial transformation. For example, a transformation scenario that requires radical change[1] in a turbulent context may require that firms become greater risk takers in search of sustainable solution, whereas a longer term transformation scenario may formulate policy in terms that improve the ecological education of the public in hopes that consumer decisions will eventually force firms improve their sustainable practice. In either case, knowledge of how contextual constraints and challenges affect organisational environmental change is critical for application of principles of industrial transformation. In this area there is to be learned a lot from the transformation processes in relation to technological innovation. In that research area it has been argued that skills and capabilities of existing companies become outdated when radical technological change occurs. This would imply that focusing on newcomers and innovators is more important then dealing with existing industrial structures (Tushman and Anderson, 1990).

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1 Radical change could be in reaction to a heavy shock to the regulatory, public relations, economic, or environmental context within which a firm operates.

Organisation and Management

The third area of organisational research that has received examination is the internal operational and management dynamics. While the process of industrial transformation could elicit an image of strict policy implementation, it is better understood as changes in the ways in which firms operate and manage their businesses.

Gladwin (1993) may be seen as a starting point for application or organisation theory trajectories to the greening of industry. He emphasises the potential of institutional, population ecology, resource dependence, strategic choice, leadership and evolutionary change models to shed light on why and how organisations adapt and change within specific contexts. Since the appearance of Gladwin's review in 1993, a number of researchers have taken his cue and a small set of theoretical pieces have emerged (see background document by Welch). Nevertheless, almost no empirical application of existing organisational theories. Shrivastava (1994) concurs, arguing that research on total quality management, ecologically sustainable competitive strategies, ecological technology transfer, and reduction of populations on ecosystems, should be reanalysed by organisation theorists in ways that provide a greater understanding of the variety of pathways corporations can take to become sustainable.

The ability to incorporate environmental concerns into the product development process is becoming increasingly important as diverse constituents make greater demands upon firms for improved environmental performance. Based on a review of capabilities literature, we propose that environmental design capability derives from expertise on environmental impacts and technologies both internal and external to the firm (knowledge resources) co-ordinated with product development teams through dense information networks (communication linkages) embedded in a context where environmental information is understood and valued. (Lenox and Ehrenfeld, 1997)

In the management literature some empirical work is devoted to the question of why and how private firms take environmental issues in consideration. Bouma (1995) and Neuman (1995) from the Erasmus University in the Netherlands provide some of the elements that seen to be important when environmental considerations are included in strategic

management. Neuman, for example, concludes from a number of case-studies that while most companies observed had environmental management structures, environmental issues were typically taken into account only in the final authorisation or implementation stages of decision making. Moreover, most decisions that had positive environmental outcomes or impacts were made for efficiency reasons. This was mainly due to the lack of environmental performance indicators at lower levels of management which are often judged only according to economic efficiency criteria. A recent study at the School of Public and Environmental Affairs at the University of Indiana asked the question "Why do firms adopt beyond compliance policies?" Using competing explanations of economic efficiency, power and leadership, researchers determined that economic efficiency based reasoning did not account for the company adoption mechanisms of many of the voluntary policies. Instead, complex and detailed power and leadership based theories seemed to provide the greatest empirical explanation for adoption of beyond compliance policies. Similar findings have been reported by Steger (1996) whom investigates human resource management and organisational learning as part of innovation oriented environmental management According to his evaluation, flat hierarchies, open communication and decentralised organisations all support innovative environmental management, while the lack of market or regulatory pressure and the monetary bias of the information system function as barriers. A paper by Fineman identifies four emotional subtexts that explain why some managers are more ecologically minded than others. They include: enacting green commitment, contesting green boundaries, defending autonomy and avoiding embarrassment (Fineman, 1996). Each is associated with how 'green' pressures are adopted, adapted or rejected. A recently published edited book by Bazerman, et. al. looks at the organisational psychology of environmental ethics and behaviour. The various chapters attempt to provide ethical and value-based reasoning behind the complex relationship humans have with the environment - on the one hand destructive and on the other preserving (Bazerman, 1997).

In the field of green accounting, environmental reporting and measurement of environmental performance initial steps have been taken that enable to investigate progress on the path of industrial transformation at the company level. In the European Union (EMS) and the US progress is made in development of accountancy methods and standardisation of approaches.(various international co-operative networks of researchers

and consultants exist) However, it still is a sub-area that lacks in progress, in part because methods for accounting, reporting and measurement are still under development, and there is not a large sample of companies for which progress can be measured on a sufficiently long time interval (Gijtenbeek, Piet and White, 1996). In addition to regulatory pressures, financial institutions, individual investors and other interest groups have a key part to play in influencing corporate environmental policy through their investment decisions (Ryall and Riley, 1996).

From a more practical perspective, attention to environmental management issues for companies has been encouraged through the ISO 14000 family of environmental management standards (EMS). Participation in any of these environmental standards is voluntary, while acceptance of core EMS standard, ISO 14001, is initialised through declaration of a firm-level environmental policy and the creation of a process to put this policy in place. An audit of the organization's EMS by independent certified auditors is a prerequisite for achieving certification (Coscio, 1996; Quality, 1996). The ISO standards on environmental management and environmental auditing are complemented by standards on environmental labelling (ISO 14240/23), environmental performance evaluation (14031/32), and life-cycle assessment (14040/43) Those standards specify general guidelines for national programs like the German Blue Angel and US Green Seal eco-labels initiatives Nevertheless, comprehensive review and assessment of the breadth of interest in these programs is rare. A first broader discussion can be found in Sheldon, 1997.

Environmental management research for the public and non-profit sectors has received limited attention Examples of the public management perspective include analysis by Bozeman and others at Georgia Institute of Technology to determine how new environmental policy affects the degree of 'red tape' in public organisations. Red tape is generally defined as delay, which is especially pronounced in public organisations. This study investigates the effect that new rules requiring public access to compliance data have on the ability of public organisations to manage implementation of policy Other work by Welch begins by developing a measure for comparative analysis of simultaneous environmental-economic efficiency. It then explores how policy contexts and administrative styles affect firm-level environmental behaviour in the US chemical

manufacturing industry. A final example is a theoretical piece by Merdinger describing how new designs for public organisations must be developed for purposes of ecosystem management may also be included here. Again industrial transformation is not limited to industry. Public and non-profit organisations, whether they act as regulators or as advocates are an equally important consideration in long-term as well as short-term encouragement for sustainability.

Industrial Structure and Network Analysis

The fourth area of research, industrial structure, not only includes traditional dimensions of vertical and horizontal relationships among firms within the same industry, it also refers to the relationships or networks among firms of different industries Multiple industry and multiple sector interactions as they relate to support for or restraint of sustainable practice are particularly salient. Work by Lynn points to the role that financial institutions play through their decisions to support business ventures in promoting or blocking sustainability (Lynn, 1996). David Dittman has noted the significant changes in the hotel industry toward environmental practices that have important up-stream effects on the manufacturing sector (Dittman, 1996). For example, alterations in the packaging systems for soaps in hotels could create a variety of up-stream and down-stream incentives and disincentives that will be played out in the market. This type of interaction among firms hints at two important facts. First, the network structure is broader than manufacturing firms alone - it includes substantial acquiescence, neutrality, encouragement or leadership from firms in the service sector. The extent to which the service sector provides leverage for sustainable change will depend upon the industry and the policy. Second, industrial transformation concerns the fundamental value and behaviour structures that exist within society. Firms in one particular industry, are often fundamentally intertwined with the complex relationships that exist between manufacturers, financial institutions, insurers, labour organisations, and education institutions that represent significant underlying value structures and patterns of expected behaviour. Change in one means by definition, change in each. The system of producer-supplier linkages, recently a target for analysis and policy design, should be broadened to include financial, insurance and other service industries. This is especially true when the service industries are often at either end of the manufacturing process.

In addition, Geiser and Crul point to the fact that much of the current systems based work on industrial greening is technically oriented (material-flow or process- based). While important, non-technical processes such as communication and decision making deserve equal attention. In some cases it may be true that the more linear and computational-friendly process based systems analysis of organisations can be directly overlaid onto the internal systems of decision and communication. However, these cases are rare. It is more typical that the temporal, spatial, and managerial overlap between the three is moderate to slight. As a result, concentration on one without consideration of the other processes and systems existing within firms has only limited value. Their observations are equally applicable to the industry or sector level where information, legal, financial, communication, power and decision making dynamics may drive and probably do override material considerations. Attention should be given to some of the recent work done by Taylor in this regard (Taylor, 1995, 1996) As a result, inclusion of other types activity and motivation is essential for understanding how the comparatively rigid technology-based processes can be enhanced, or act as barriers to industrial transformation.

The field of network analysis has grown as has the extent to which organisations have formed formal partnerships and alliances, and informal relationships. Multiple motivations for the development of interorganizational relationships have been offered in the network literature. Some of these include: risk sharing, access to new markets and technologies, shorter lead times for new products, learning, and complimentary skill sets (Kogut, 1989; Kleinknecht and Reijnen, 1992; Hagedoorn, 1993; Mowery and Teece, 1993; Eisenhardt and Shoonhooven, 1996; Powell, Koput and Smith-Doerr, 1996). Most of these rationales have positive implications for competitiveness of the firms involved. Application of these perspectives to sustainability may or may not find a similar set of rationales leading to competitive outcomes. One aspect concerns the role of networks in industrial ecology and the position of large and small firms. For instance, larger companies, often being more centrally located, have greater changes at identifying and attracting other businesses which they can co-operate with in finding usage for their wastes. The 'cluster' properties of efficient ecosystems can therefore be a limiting factor in the development of such systems (Andersen, 1997).

Within the greening literature, relationships among firms seem to be receiving the most attention as they relate to tools for implementation of industrial ecology. Steger notes that intra-sectoral cooperation is a requisite condition for successful implementation of life-cycle analysis tools. This is evident because LCA requires supply and output chains to be tightly linked among firms. A small set of articles covered by Steger's literature review point to the beginnings of theoretical investigation into the motivations and processes of network formation and activity (strategic cooperation in his terms) as they pertain to LCA (examples include Cramer and Schot, 1993; Dillon and Baram, 1993; den Hond and Groenewegen, 1993; and Drumwright, 1994). Hall and others have also looked at the strategic interdependencies among organisations and their implications for competitiveness and relationships with stakeholders (Hall, 1995; Hall and Ingersoll, 1994). While the environmental outcomes of such ecological oriented networks are supposed to result in tighter value and supply chains, much of the literature on networks also point to significant by products of higher community trust (Sweeny, 1996; Simons and Wynne, 1993, Lynn and Chess, 1993) and reduction of external turbulence (Trist, 1983).

Much of the research in the area of network analysis in the social sciences considers organisational networks as embedded within social systems, but little of it incorporates considerations of the physical environment into the models. Questions currently ignored include the following: When are network alliances made solely on the basis of environmental objectives? How are environmental motivations absorbed or removed over time? To what extent does network formation - for the purposes of stabilising turbulent environments and building trust with the community - lead to longer-term stalling and delays in sustainable transformation?

Public sector research, both as a response to increased interorganizational activity among the different sectors, and in reaction to an increased emphasis on networks in the private sector literature, has also spawned its own network theorists. While many of the private sector motivations for networks also pertain to inter-sectional networks, additional motivations have been put forward for the public sector. Some of these include sharing resources for improved policy implementation; greater input into policy design and implementation decisions; greater knowledge about successes and failures; and increased

consistency of policy design and adoption. The complex multi-actor processes for the identification, definition, and resolution of policy problems, as well as for the implementation of environmental policy have been explored over the years by a number of researchers with interest in public and non-profit organisations. A series of articles exploring interorganizational relationships with respect to implementation for water policy appeared in the journal Environmental Politics in 1994. The findings essentially indicate that "network structures are increasingly important in substantive terms, and an adequate understanding of policy action (and inaction) in many nations requires a recognition of the causal impact of these multiunit structures (Bressers, O'Toole, and Richardson, p. 6, 1994)."

Research conducted at the Vanderbilt University (USA) on the influence of local communities on firms that have published their environmental profiles through the toxic release inventory (TRI) provides insights into how open information has provided a stimulus of local community to actively participate with companies on environmental issues, although the effects on reducing pollution is highly influenced by the local community characteristics. Mechanisms through which the local community exerts pressure on companies vary from direct negotiation, to the forming of action committees, to spreading of information to stock exchange markets: (The role of stock markets and financial institutions such as banking and insurance industries in network analysis may deserve more attention in future research.) Does this type of open public process react positively or negatively with industrial transformation in the long run? In the short run? In a system of extensive public access to information, what is the effect of public participation on industrial transformation? What about in a system in which access of information is limited? Typically, greater public interest tends to fragment opinion or slow policy implementation rather than consolidate opinion or speed up the implementation process. How can public participation in a broader network benefit (hinder) the implementation of industrial transformation?

Public-private partnerships are another form of network activity. These linkages are based on voluntary acceptance of waste minimisation, energy conservation, design for environment, or other environmental standards. While a number of these programs exist in

the US[2], , little research has been done on them to determine how or if they are effectively accomplishing their goals. We know that many of these programs have been pursued as a result of limited capacity and effectiveness of government to impose regulation that coerces industry to adopt sustainable mechanisms. Other contributing factors to their apparent success include the lack of sufficient economic instruments to induce sustainable practice, a minority of public leaders calling for stronger mechanisms (Hull, 1994), and seeming industry willingness to adopt such programs. While long-term economic risk (opportunity) factors probably drive much of industry willingness to participate, other factors such as concern regarding environmental risk, ethical motivations, and political factors may have a greater impact. As a cautionary note, some recent publications remind us of the sophistication of the public relations industry and its power to influence the public, policy and peers toward or away from environmental objectives (Greer and Bruno, 1997; Stauber and Ramton, 1995) To what extent are organisations able to set up structurally sustainable informational, political and ecological barriers to sustainable transformation?

1.4 Relevance of a Focus on an Organisational And Management Perspective for Industrial Transformation

Management and organisational processes form an important intermediate category between systems level and consumption and behaviour oriented or in research terms bottom-up and top-down approaches in IT. However, research linking the chosen strategic, technological and organisational approaches to improved environmental performance has developed unevenly. Three main points need some attention in order to fit this area into the overall theme of Industrial transformation. First, the research on organisational design starts from a more or less normative perspective, results of this think work have been reported above What is lacking is information of the economic and environmental effectiveness of

2 Partnerships between governments and companies for Pollution Prevention in the US include: 33/50 program, AGSTAR, Climate Wise Recognition Program, Coal-bed Methane Outreach Program, Common Sense Initiative, Design for the Environment, Energy Star Programs, Environmental Accounting Project, Environmental Leadership Program, Green Chemistry Program, Green Lights Program, Indoor Environment Program, landfill Methane Program, Pesticide Environmental Stewardship Program, Project XL, The Ruminant Livestock methane Program, State and Local Outreach Program, Transportation Partners, US Initiative on Joint

these forms.

Second, empirical studies that cover the fit between management style and environmental performance usually of necessity leave out the effect of these styles on actual environmental performance. It seems that integrating the current activities in the area of environmental accounting and assessing the effectiveness of these for evaluation of structural change in industry is very important. Third, research on institutional and organisational influences on technology development that more or less covers the same field as Industrial Transformation has up till now not been integrated very well. The integration of the outcomes of economic and organisational studies on energy efficient behaviour could be a welcome addition to the setting the agenda for a next step of studies in industrial transformation.

While network analysis may provide some of the best clues to how industrial transformation can take place, non-systems oriented research should not be ignored. Similarly, the importance of non-technical systems should not be underestimated. While complex, this type of research promises to provide a rich, cross-disciplinary theoretical understanding which takes organisations and their interactions as levels of analysis. Understanding the motivations and dynamics of network linkages and organisational boundary changes should be a initial set of objectives for future research. As a first step, a meta analysis of these literatures and their application to industrial transformation hould be undertaken.

Implementation, Voluntary Aluminium Industrial Program, Voluntary Standards Network, Waste Minimisation National Plan, Water Alliances for Voluntary Efficiency, and Wastewise Program.

2. 5. Consumers Choice, Sustainable Consumption

Sustainable Consumption
Research aimed at understanding determinants of consumer behaviour and the associated environmental impacts from consumption
Contains.
1 Determinants of consumer behaviour (insights in consumer behaviour including consumer boycott and responses to policy actions) 2. Determination of the environmental impact of patterns of consumption (definition of what is sustainable consumption and how it relates to e.g. environmental impacts of production) 3. Stimulating sustainable consumption by purchasing policies and the 'greening' of the supply chain

Table 5: Sustainable Consumption

2.1 Introduction

The change of consumption patterns can be identified as a potential driving force in a process of transformation of the industrial economies toward sustainability and may therefore represent a key focus of a different strategy of society than directly influencing firms' behaviour and production technologies. This is especially important because any efficiency strategy to reduce the anthropogenic environmental impact potential must be accompanied by a complementary strategy of sufficiency. In fact if the consumption of material goods and that of material intensive services rises, the efficiency gains in production may be "eaten up" by increasing consumption (Sachs, 1993; Spangenberg, 1995). Insight in how people spend their money if they become more affluent is a necessary condition to understand industrial transformation.

The report of the Oslo Ministerial Roundtable defines sustainable consumption as an "umbrella term that brings together a number of key issues, such as meeting needs, enhancing the quality of life, improving resource efficiency, increasing the use of renewable energy resources, minimising waste, taking life cycle perspective and taking into

account the equity dimension" (Miljoverndepartementet Norway 1995). The issue of sustainable consumption patterns as such is not new. Governments, companies and NGOs have indeed focused their strategic goals, and crucial elements of the broader sustainable development agenda. The North-South tensions that marked the negotiations of the Agenda 21, chapter 4, on "Changing Consumption Patterns" have recently given way to a more pragmatic debate. Yet integrated scientific efforts are still scarce.

Scientific research aimed at promoting IT through making consumption sustainable has the dual task of coming up with a definition of what is sustainable consumption and answering the question of how current consumption patterns can be changed into the desired direction. The latter requires insight in the determinants of consumer behaviour as well as the possible responses of consumers to policies that directly or indirectly influences them (Section 5.2.). The former must investigate the differences in the repercussions on the environment of different patterns of consumption (*environmental impact of consumption patterns*, Section 5.3.). These two aspects can obviously be separated only for analytical purposes; a synthesis is needed. Perhaps this focusing on the consumer as 'a responsible individual who makes deliberate choices regarding the environmental impact of his/her daily routines' is too large a responsibility. Meijkamp (1997) concludes that most instruments of motivational, economic and psychological nature for regulating consumer behaviour have largely failed. Additional strategies for promoting sustainable consumption may be developed by authorities in 'green purchasing' programs, and by companies that offer environmentally responsible products and services, promoted by 'green marketing' in a narrow sense (Section 5.4.).

2.2 Determinants of consumer behavior

Approaches to describe consumer behaviour can be found in economic, psychological, sociological and biological literature. Consumption is an umbrella issue also from a scientific point of view: to understand consumption issues, economic, psychological, sociological *and* biological knowledge is important. Hence we need information about the underlying models of consumers behaviour as well as of the consumption-environment interaction (societal metabolism). Societal, economic, political, geographical dimensions

need to be specified. Another differentiation can be made according to basic consumption, quantity and qualities of consumption.

But most of the literature capturing consumption and the consumption-environment interrelation to date is mutually exclusive.

- In economics, microeconomic theory of individuals behaviour deals mainly with (rational) choice in a given (and highly abstract) economic environment. Determinants considered are mainly market oriented Reference can be made to any microeconomic text book (see Luckenbach 1982, 1986 and Yavuz 1995)
- Psychological authors stress behavioural aspects, such as imitative behaviour, motivation, empathy or education (see Fietkau 1984, Kapp 1988, Scherhorn 1993, 1997).
- Sociological literature focuses on societal determinants such as social position, family size and composition, habits and social rules (see Aumann 1996, von Winterfeld 1996, Scherhorn 1993).
- Biology stresses physiological needs, inherited behaviour and reproductive traits (see Scherhorn).
- Consumer research and marketing studies investigate empirically and theoretically the demand behaviour of individuals and households in the formal markets.
- Finally, anthropologists look at the behaviour of individuals and groups as depending on their geographical and cultural environment (see Strassert 1996).

All this disciplinary work has not delivered sufficient answers to a good understanding of the area of sustainable consumption. Nevertheless a number of attempts have been made in order to transcend the boundaries of disciplinary work:

- Consumer economists such as Gerhard Scherhorn (1993, 1997) look at the impact of values, addiction and institutional regimes.
- Evolutionary economists look at preference formation, the mutual interdependence of preferences and market results (see Hinterberger 1992) and the socio-biological roots of consumption patterns (see Penz 1993, Jendrosch 1995).
- Structural economists (such as Schor 1995 and Roepke 1994) investigate consumption in the framework of work and spend cycles;

Several of the numerous people working in the field include: Loren Lutzenhiser, sociologist at Washington State University (USA), Willett Kempton at the University of Delaware (USA), Paul C. Stern at the US National Research Council, Lee Schipper at the Lawrence Berkeley National Laboratory (USA), Charles Vlek (Rijksuniversiteit Groningen, Netherlands), Peter Ester, Cees Midden, Fred van Raaij (all three at Dutch Universities), Ragner Lofstedt (Surrey, UK), Mark van Vugt (Southampton, UK), George Gaskell (London School of Economics, UK), John Thogerson and Folke Olander (both at Aarhus School of Business, Denmark), and Heinz Gutscher (University of Zurich, Switzerland).

Box 7: Several of the numerous people working in the field of consumer behaviour.

We acknowledge that the above is somewhat biased to the non-English literature. Additional references that the interested reader may turn to for further insight are: Lutzenhiser (1993), National Research Council (1997), Stern (1992), Stern and Aronson (1984) and Stern and Oskamp (1987). A general source, which provides a conceptual framework and overview of the literature at the household level, is Gardner and Stern (1996). Two recent compilations of work on consumerism generally, with some attention to environmental issues are Goodwin et al. (1997) and Crocker and Linden (1998).

For an overview of several of the numerous people working it is referred to box 7.

2.3 The environmental impact of consumption patterns

In addition to an understanding in the aspects of consumer behaviour we need a comprehensive (theoretical and empirical) understanding of how environmental change can be attributed to specific household/ consumption activities (see Behrensmeier and Bringezu 1996, Strassert 1996, Wackernagel and Rees, 1996). Interesting work, although restricted to

description, is being done at the LCA interface with regard to the environmental impact of specific every-day products, such as hamburgers, cigarettes, bananas, paper clips, bleu jeans, etc. (Cousteau, 1981; Ryan and During, 1997; ULS, 1996). Still, a comprehensive study of the impact of consumption patterns and lifestyle on the environment and how these could be changed is out of sight, which is partly to do with issues of methodology and definitions. A few examples have been attempted, however: studies such as Sustainable Europe and Sustainable Germany look at the development of new paradigms for consumption (in terms of well-being instead of well-having, see Spangenberg, 1995, BUND/ Misereor 1996), economists and natural scientists that work together in the area of household metabolism (IVEM, Groningen).

One particular issue is related to international trade. Ongoing changes the spatial dislocation of industrial activities make that a country's production/ consumption could appear greener just because some of the necessary extraction and processing activities (and so the corresponding environmental burden) are exported to other countries. The "environmental footprints" literature (Wackernagel and Rees, 1996) addresses these issues as well as the notion of "Total Material Input" or "ecological rucksacks" as developed at the Wuppertal Institute (see Bringezu 1995). With these concepts the focus on consumption allows to overcome the difficulties arising from the spatial mobility of production and constraints on the production side that can lead to a mere translocation of production; the change of consumer behaviour enhances production wherever it takes place.

A related aspect in the determination of a sustainable consumption pattern deals with the question of how much influence consumers can exert on the environmental aspects of consumed goods and services. As far as the emissions directly connected to consumption activities are concerned (direct intake of resources from consumers are a minor phenom-enon), the relevant actors are not only the consumers: the "use technology" built into the products or the services is rarely under their complete control. Other problems, also relevant for eco-labelling, refer to the fact that all the inputs and outputs to the environment caused by the production processes are relevant for the final environmental impact of a consumption good. Hence information on these inputs and outputs are necessary in order to determine the environmental cost of the consumption activity. Consumers, however, lack

most of the information necessary to assess the relative environmental significance of different production processes - in order to trace back to the environment/ technosphere border the effects of different consumption patterns, an ideal "vertical integration" (Pasinetti, 1973) of the production processes must be performed. Thus, once again, an active role in promoting environmentally-friendly consumption must be played also by other actors besides consumers. The material-product chains described in Section 2.5. may be relevant for this area of research too.

2.4 Stimulating sustainable consumption

Public procurement (section is based on Van der Grijp, forthcoming)

Public procurement refers to processes of purchasing and tendering by public authorities, aimed at facilitating the fulfilment of public duties. Four different areas of public procurement can be distinguished:

product supply contracts—paper, writing utensils, computers, photocopiers, office furniture;

service contracts—cleaning, maintenance, catering, waste removal activities;

public work contracts—building and construction of housing, public facilities, roads, hydraulics;

contracts in the utility sectors—water, energy, transport, telecommunications.

The economic value of public procurement is considerable. Among OECD countries governmental consumption of products and services amounts to 5-15 percent of Gross Domestic Product; about three quarters of the expenses are on products and services, while the remainder is on the acquisition of capital goods (OECD, 1997). Given the sheer volume of public procurement expenses, public purchasers may influence the markets for environmentally sound products and services in several ways (Oosterhuis et al, 1996):

directly, by demanding products and services with a lower overall environmental impact;

indirectly, by putting pressure on producers to develop products and services with a lower environmental impact; indirectly, by improving the market position of environmentally preferable products and services indirectly, by setting an example for other consumers.

The potential of public procurement as an instrument for environmental policy has been recognised by public authorities from several countries and international organisations. The European Commission, for example, states that "the role of public procurement policies as they affect the environment needs to be considered by all levels of administration" (CEC, 1996). The OECD has given a high priority to a "green" public procurement and recommends that member countries "establish and implement policies for the procurement of environmentally sound products" (C(96)39/FINAL). However, several issues remain to be solved in relation the continuing process of formalising tendering practices in order to ensure open and transparent competition among potential bidders, such as the procedural rules issued by GATT/WTO and the EU (COM(96)583 final). It is unclear whether these emerging, more complicated regulatory frameworks on public tendering will prove to be obstacles to the greening of public procurement. Alternatively, neither is the present framework a stimulating factor, and it certainly does not provide an invitation for a revolutionary approach to the greening of public procurement.

Although the issue is highly debated in (inter)national bodies, research is still scarce. Van der Grijp (1995) has evaluated the greening of public procurement in the Netherlands. According to the National Environmental Policy Plan of 1990, public authorities should fulfil an exemplary function in environmentally sound behaviour which extends through the 'greening' of public procurement. The emphasis in the Dutch discussion has been on the substitution of products and services by environmentally preferable ones, but, according to pioneers in the field, the discussion should take a new turn; the crucial issue is to reduce the amount of products used. Van der Grijp found several barriers to be overcome:

- the willingness to do something about the environmental problems connected to public consumption patterns is largely dependent of individuals;
- the cost of alternative products is often, but not always, higher than conventional products, depending on the method used for cost-benefit analysis.

- in some cases the dominant market position of major suppliers has been an obstacle to the breakthrough of environmentally sound products;
- information barriers refer to the availability and quality of product information, including their environmental characteristics;
- legal barriers exist in the procedural framework of national and international regulations, for example the EU public procurement procedures and the sanctions connected to non-compliance (Van Scheppingen, 1995);
- the lack of appropriate organisational procurement competencies and structures limits communication and exchange of information within and across public administrations;
- technical barriers exist in the (perceived) quality and characteristics of environmentally sound products and their market availability—establishing product standards and certification may help in solving this problem.

Further information is to be found through the OECD in the "Greener Public Purchasing Issues Paper" and the European Green Purchasing Network which is supported by CEC DGXI, EPE and ICLEI.

Greening the supply chain

Greening the supply chain is the second sub-theme addressing the stimulation of sustainable consumption. It raises questions of how companies offer the customer a greener product by imposing improved environmental performance of their suppliers (Morton et al., 1997). Many examples of industrial firms have been described (compare with Section 3.4. on life-cycle design) and the opportunity is increasingly recognised for agricultural products too (Groenewegen et al., 1997; Maier et al., 1997; Michelsen, 1996). In addition to the well-known examples of food retailers such as Sainsbury, Tesco, Albert Heijn, Migros Coop, airlines start to cater biologically produced food on board of their flights[3] Chouinard and Brown (1997) provide a very informative view of the implementatio process and consequences of a company's decision to substitute organically fc conventionally grown cotton. The main argument in promoting a greening of the suppl chain is that probably (big) businesses will be more effective in reaching small business

3 See "Swiss airline goes organic", Panups Press Release of August 15, 1997 (http://www.panna.org/panna, panupdates@igc.apc.org).

with the message of environmental management, especially in developing countries[4]. However, many small companies have trouble in finding adequate technical assistance for implementing cleaner production techniques (ibid.).

Green marketing (section is based on Mauser, 1996)

Environmental or 'green' marketing has only be considered a separate field since the late 1980s With the rise of environmental awareness among consumers, many companies marketed so-called 'green' products, sometimes misleadingly so. 'Environment' was an additional feature for enhancing the objectives of 'traditional' marketing. However, 'marketing' may also be used to promote objectives of reducing environmental impact. This conception of green marketing is routed in the concept of 'societal marketing', developed during the 1970s. E.g. Kotler (1988) argues that strategic marketing should not only be targeted at meeting direct consumer needs and increasing the company's profits, but also at increasing welfare in society at large. Thus, there are two conceptions of green marketing to be found in the literature. However, the two conceptions need not be opposites; they can be brought together in a working definition:

Environmental marketing comprises all activities aimed at generating and facilitating market exchanges in order to meet the needs and interests of consumers and other stakeholders, while minimising environmental impacts to as low as reasonably achievable levels (Mauser, 1996:71).

Environmental marketing may be discussed in a narrow sense, and as a multi-disciplinary, integrate approach. In a narrow sense, environmental marketing aims at stimulating environmentally sound consumer behaviour. Eco-labels and environmental certification of products and processes are important instruments in this respect, as is a thorough understanding of determinants of consumer choice. Green products may be sold to a wider group of consumers than the 'eco-diehards' if marketeers succeed in overcoming various barriers, such as (1) non-acceptance of environmental responsibility, (2) non-observance of environmental impacts of behaviour, (3) lack of knowledge about cause-effect relationships between behaviour and environmental impact, and (4) high opportunity cost of adoption of

4 SeeBurton Hamner, March 20, 1997 on discussion list ecdm@pdomain.uwindsor.ca).

environmental responsible behaviour (time, efforts, attitudes) (Driessen and Verhallen, 1995). However, if companies manage to add additional value to products and services by reducing their environmental impact, considerable commercial opportunities may loom.

Considering environmental marketing as a multidisciplinary, integrative field makes use of the so-called 'marketing mix' which comprises the integration of environmental issues in the various aspects of the product/service itself, the price, location, and advertisement. For example, environmental marketing extends to LCA eco-design and chain management when considering aspects of the product/service. Considering price, it would include costs of use and disposal in addition to purchasing cost. Considering location, environmental impacts of disctribution, packaging, recycling, and transportation would be relevant aspects. Finally, promotion would extend to a credible 'green' corporate reputation and image, and aim at stimulating and reinforcing certain life styles.

An extension to this view of environmental marketing is the voluntary collaboration between companies and environmental NGOs to pursue mutually beneficial ecological goals. Several American examples of such 'green alliances' have been collected by Stafford and Hartman (1996). They include the well-known alliance between McDonald's-EDF alliance for the reduction, re-use and recycling packaging material. For multinationals such as Shell and Exxon, the disastrous experiences of respectively the Brent Spar disposal and the Exxon-Valdez oil spill were reasons to engage in dialogue and cooperation, rather than confrontation, with environmental groups. Such alliances have a strategic importance as they allow businesses to gain insight in the environmental objectives of leading stakeholders at early stages, to incorporate those in corporate and business strategies, and thus to prevent the antagonistic relationship that has prevailed for so long. For NGOs, such alliances are a means to stimulate companies to move beyond compliance. However, not all such alliances have become a success. How companies use such alliances and whether indeed they are able to regain legitimisation are questions for further research.

Many authors have written on environmental marketing, including Paul Driessen at Tilburg University in the Netherlands, Cathy Hartman and Edwin Stafford at Utah State University,

John Elkington, at SustainAbility Ltd., London, and Ed Peelen at the University of Amsterdam.

Important journals include the *Journal of Public Policy & Marketing* (special issue in Fall 1991), *Journal of Business Research* (special issue in May 1994), *Journal of Advertising* (special issue in Summer 1995), and the *Journal of Marketing*.

2.5 Relevance of the research on sustainable consumption for IT and research gaps

The area of sustainable consumption is obviously of importance for an IT-program, since it provides insight in one of the main driving forces of the relationship between society and the environment and it is one of the elements of structural transformation that has been defined in the Scoping Report. There exists a close linkage between the spatial composition of production and consumption through international trade. "Environmental footprints" literature addresses these issues.

Nevertheless there have been no systematic efforts that address the issue of sustainable consumption in a coherent framework. Such efforts should be oriented to

analysing the material/energy consumption that can be attributed to specific consumption activities of households; analysing the interrelation between production and consumption in the light of endogenous preferences, institutions, life-styles, marketing as well as international trade; what are the tendencies towards dematerialisation of production and what are the barriers; investigations into the role of values and ethics, collective action and consumer sovereignty; investigations into the connection of consumption with work, employment and leisure.

The current fragmentation of scientific knowledge of consumption behaviour (as high-lighted above) should obviously be overcome and the unity of the subject (human beings, not just consumers) recomposed. This not just for ontological reasons, but mainly because any effective policy on such an important matter as making consumption sustainable can

only be attained if the determinants of the behaviour of people in their role of consumers are sufficiently understood. This implies that all disciplines' insight should be integrated when treating this aspect of the problem. The other main piece is the systemic understanding of the causation mechanisms which lead from a certain consumption pattern (however determined) to its corresponding environmental burden.

Additionally, there is considerable scope for developing theory-in-action in stimulating greener consumption. If a direct change of consumer behaviour proves hard to realise, indirect routes could be explored, several of which have been discussed. Strategies include approaches to create a sufficient demand for green products in order for markets to materialise, clean up of production chains, and 'intelligently' addressing consumer needs.

3. References

Adriaanse, A., S. Bringezu, A. Hammond, Y. Moriguchi, E. Rodenburg, R.Rgich and H. Schuetz (1997). *Resource Flows the Material Basis of Industrial Economies*. World Resources Institute/wuppertal Institute, Netherlands Ministry of Housing, Spatial Planning and Environment/ National Institute for Environmental Studies.

AIPP (1993), *A Primer for Financial Analysis of Pollution Prevention Projects*. EPA/600/R93/059. US Environmental Protection Agency. Washington, DC.

Alcamo, J., R. Shaw and L. Hordijk (eds.) (1990), *The RAINS Model of Acidification: Science and Strategies in Europe*. Dordrecht, The Netherlands: Kluwer Academic Publishers.

Alting, L. and J. Jørgensen (1993), The Life Cycle Concept as a Basis for Sustainable Industrial Production, *Annals of the CIRP Vol 42/1/1993*, 163-167.

Alting, L. and J.B. Legarth (1995), Life Cycle Engineering and Design, *Annals of the CIRP* 44/2:1-11.

Andersen, O. (1997), Industrial Ecology and some implications for rural SMEs. *Business Strategy and the Environment* 6: 146-152.

Andrews, C., F. Berkhout, and V. Thomas (1994), The Industrial Ecology Agenda, In: R. Socolow, C. Andrews, F. Berkhout and V. Thomas (eds.), *Industrial Ecology and Global Change*, Cambridge University Press.

Arrow, K., Bolin, B., Constanza, R., Dasgupta, P., Folke, C., Holling, S., Jansson, B.-O., Levin, S., Mäler, K.-G , Perrings, C., and D. Pimentel (1995), Economic growth, carrying capacity, and the environment, *Science* 268: 520-521.

Arthur, W.B. (1989). 'Competing Technologies, Increasing Returns and Lock-in by Historical Events', *Economic Journal*, 99.

Ashford, N.A (1993), Understanding Technological Responses of Industrial Firms to Environmental Problems: Implications for Government Policy, In: K. Fisher and J. Schot, *Environmental Strategies for Industry*, Island Press, Washington, D.C.

Aumann, R. (1996), Anforderungen zur Überwindung der vorhandenen geschlechtlichen Arbeitsteilung in ökologischer Perspektive. Studie erstellt in Auftrag des Wuppertal Institutes für Klima, Umwelt, Energie GmbH, Oktober 1996.

Ayres, R.U. (1989), Industrial metabolism. In: Ausubel and Sladovich (eds.), *Technology and Environment*, National Academy Press, Washington, D.C., pp.23-49.

Ayres, R.U. and A.V. Kneese (1969), Production, Consumption and Externalities. *American Economic Review* 59: 282-297.

Ayres, R.U., L. Ayres and K. Martinès (in press), Eco-Thermodynamics: Exergy and Life-Cycle Analysis, *Energy*.

Ayres, R.U. and U.E. Simonis (eds.) (1994), *Industrial Metabolism: Restructuring for Sustainable Development*, United Nations University Press, Tokyo.

Baba, Y., M. Yarime and H. Hatashima (1997), Realising the shift towards closed-loop recycling: Strategies of the Japanese firms, *International Journal of Innovation Management* 1 (1), 89-110.

Barney, G.O. (1980), *The Global 2000 Report to the President of the U.S.: Enterning the 21st Century*, Volume I, Volume II. Pegamon Press, New York.

Behrensmeier, R. and S. Bringezu (1995): *Zur Methodik der volkswirtschaftlichen Material-Intensitäts-Analyse: Der bundesdeutsche Umweltverbrauch nach Bedarfsfeldern*. Wuppertal Institut, Wuppertal Papers Nr. 46.

Van den Bergh, J.C.J.M. (1996), *Ecological Economics and Sustainable Development. Theory, Methods and Applications*. Edward Elgar Publishers, Brookfield, US.

Berkhout, F. (1996), Life cycle assessment and innovation in large firms, *Business Strategy and the Environment* 5: 145-155.

Bouma, J.J. (1995), *Environmental Care in the Dutch Royal Air Force and in Industry*, thesis, Centre for Environmental Studies, Erasmus University, Rotterdam, The Netherlands.

Bovenberg, A.L. and S. Smulders (1995), 'Environmental Quality and Pollution-Saving Technological Change in a Two-Sector Endogenous Growth Model', *Journal of Public Economics*, 57, pp. 369-391.

Bressers, H. and L.J. O'Toole, Jr. (1994), Networks and Water Policy: Conclusions and Implications for Research, *Environmental Politics* 3, 197-217.

Bressers, H., L.J. O'Toole, Jr. and J. Richardson (1994). Networks as Models of Analysis: Water Policy in Comparative Perspective. *Environmental Politics* 3, 1-23.

Bringezu, S. (ed.) (1995), Neue Ansätze der Umweltstatistik: Ein Wuppertaler Werkstattgespräch. Wuppertal Texte, Basel u.a.: Birckhäuser.

De Bruyn, S.M. and S. Anderberg (1997), Industrial Transformation: System Analytical Perspectives on the Macro Scale, Background paper, IHDP-IT no.6.

BUND/Misereor (Hrsg.) (1996), *Zukunftsfähiges Deutschland. Ein Beitrag zu einer nachhaltigen Entwicklung*, Studie des Wuppertal Instituts. Basel, Boston und Berlin.

Cascio, J. (1996), *Conformity Assessment for EMS and EL Case for International Harmonization*. http://www.stollen.com/isofiles/cascio.htm#Cascio2.

Chouinard, Y. & M.S. Brown (1997), Going organic: Converting Patagonia's cotton product line, *Journal of Industrial Ecology* 1 (1) 117-129.

Commission of the European Communities (1996), Public procurement in the European Union: Exploring the way forward. Green Paper. COM(96) 583 final. Brussels, Belgium.

Consoli, F., D. Allen, I. Boustead, J. Fava, W. Franklin, A.A. Jensen, N. de Oude, R. Parrish, R. Perriman, D. Postlethwaite, B. Quay, J. Seguin, and B. Vigon (1993), *Guidelines for Life-Cycle Assessment: A "Code of Practice"*, Society of Environmental Toxicology and Chemistry, Pensacola, FL, and Brussels, Belgium.

Cousteau, J.-Y. (1981), *The Cousteau Almanac - An Inventory of Life on Our Water Planet*, Cousteau Society.

Crocker D.A. and T. Linden (eds.) (1998), *Ethics of Consumption: The Good Life, Justice, and Global Stewardship*. Lanham, MD: Rowman and Littlefield.

Cramer, J. (1996), Experiences with implementing integrated chain management in Dutch industry, *Business Strategy and the Environment* 5 (1), 38-47.

Cramer, J. and J. Quakernaat (1994), Methodology for implementation of integrated chain management at company level, *Journal of Clean Technology and Environmental Sciences* 4: 139-149.

Cramer, J. and J Schot (1993), Environmental Co-makership Among Firms as a Cornerstone in the Striving for Sustainable Development, in: K. Fischer and J. Schot (eds.), *Environmental Strategies for Industry International Perspectives on Research Needs and Policy Implications*. Washington, D.C.: Island Press.

Dillon, P.S. and M.S. Baram (1993), Forces Shaping the Development and Use of Product Stewardship in the Private Sector, in: K Fischer and J. Schot (eds.), *Environmental Strategies for Industry International Perspectives on Research Needs and Policy Implications*. Washington, D.C.: Island Press.

Driessen, P.H. and T.M.M. Verhallen (1995), Marketing, consument, en milieu, *MAB* (April) 189-197.

Van Drunen, M. (1997), *Het nut van LCA's in het bedrijfs- en overheidsbeleid en inventarisatie van wensen van bedrijven*, IVM research report W97/16, Vrije Universiteit, IVM, Amsterdam.

EPA (1994), International (non-US) industrial pollution prevention : a case study compendium. Office of Water, US Environmental Protection Agency, Washington, D.C.

Erkman, S. (1994), Ecologie industrielle, metabolisme industriel et societé d'utilisation. Etude effectuée pour la Foundation pour le progres de l'homme, Geneva, Switzerland.

Faber, M. and J.L.R. Proops (1990), *Evolution, Time, Production and the Environment*. Berlin/Heidelberg: Springer-Verlag.

Fietkau, H.J. (1984). Bedingungen ökologischen Handelns - Gesellschaftliche Aufgaben der Umweltpsychologie. Weinheim: Beltz-Verlag.

Femia, A. (1996). Sostenibilià ed uso di materiali. Tesi finale del Dottorato di Ricerca in Economia Politica. Università degli Studi di Ancona.

Fischer, K. and J. Schot (eds.), *Environmental Strategies for Industry: International Perspectives on Research needs and Policy Implications*, Island Press, Washington (D.C.).

Freeman, H.M. (1995), *Industrial pollution prevention handbook*, McGraw-Hill, New York.

Freeman, H.M., T. Hart, J. Springer, P. Rando, M.N. Curran and K. Stone (1992), Industrial Pollution Prevention: A Critical Review *J. Air and Waste Management Association* 42 (5), 618-656.

Frosch, R.A. (1995), The industrial ecology of the 21st century, *Scientific American* 273 (3), 144-147.

Frosch, R.A. and N.E. Gallapoulos (1989), Strategies for manufacturing, *Scientific American* 261 (3), 94-102.

Fuchs, D.A. and D.A. Mazmanian (1997), The Greening of Business: Needs of the Field, paper at the sixth Greening of Industry Network conference, Santa Barbara (CA), November 16-19, 1997.

Gardner, G.T. and P.C. Stern (1996), *Environmental problems and human behavior*, Needham Heights, MA: Allyn & Bacon.

Geier, K. and Crul, M. (1996), Greening of Small and Medium-sized Firms: Government, Industry and NGO Initiatives. In: P. Groenewegen, K. Fischer, E.G. Jenkins and J. Schot (eds.), *The Greening of Industry Resource Guide and Bibliography*. Island Press, Washington, DC. pp 213-244.

Georgescu-Roegen (1971), *The Entropy Law and the Economic Process*. Cambridge, Mass: Harvard University Press.

Gertler, N., and Ehrenfeld, J. (1996), A Down-to-Earth Approach to Clean Production. *Technology Review* 99 (2): 48-54.

Gijtenbeek, M., J. Piet and A.L. White (1996). The Greening of Corporate Accounting. In: P. Groenewegen, K Fischer, E.G. Jenkins and J. Schot (eds.) (1996), *The Greening of Industry Resource Guide and Bibliography*, Washington, D.C.: Island Press, p137-167.

Gladwin, Thomas N. "The Meaning of Greening: A Plea for Organizational Theory." In Johan Schot and Kurt Fischer, *Environmental Strategies for Industry: International Perspectives on Research Needs and Policy Implications*. Washington, D.C.: Island Press. 1993.

Gladwin, Thomas N., James J. Kennelly, Tara-Shelomith Krause (1995). Shifting Paradigms for Sustainable Development: Implications for Management Theory and Research. *Academy of Management Review* 20 (4), 874-907.

Goodwin, N.R., F. Ackerman and D. Kiron (eds.) (1997). *The Consumer Society*, Washington: Island Press.

Golove, W.H (1994). Are investments in energy efficiency over or under?· An analysis of the literature. *Proceedings of the ACEEE Summer Study on Energy Efficiency in Buildings* American Council for an Energy-Efficient Economy, Washington, DC.

Golove, W.H., and Eto, J.H. (1996), *Market barriers to energy efficiency A critical reappraisal of the rationale for public policies to promote energy efficiency*. Lawrence Berkeley Laboratory LBL-38059, Berkeley, CA.

Gowdy, J.M. (1994), *Co-evolutionary Economics. The Economy, Society and the Environment.* Dordrecht: Kluwer Academic Publishers.

Greadel, T.E. (1994), Industrial ecology: Definition and implementation. In: R. Socolow et al. (eds.), Industrial Ecology and Global Change, Cambridge University Press, Cambridge (MA), pp.23-41.

Greadel, T.E. & B.R. Allenby (1995), *Industrial Ecology*, Prentice Hall: Englewood Cliffs (NJ).

Graedel, T.E., B.R. Allenby, and P.R. Comrie (1995), Matrix Approaches to Abridged Life Cycle Assessment, *Environmental Science and Technology* 19(3):134A-139A.

Van der Grijp, N.M. (1995), *Product policy and the environment: the example of public procurement*. R-95/4, VU University Press, Amsterdam, The Netherlands.

Van der Grijp, N.M. (forthcoming), Greening of public procurement: the case of the Netherlands. In: Trevor Russell (ed.), Greener Purchasing, Greenleaf Publishing, Sheffield, UK.

Groenewegen, P., E.M. Reijnen and T. Goverse (1997), Reduction of pesticide use in the Netherlands: What leverage for policy?, *European Environment* 7: 126-132.

Groenewegen, P., K. Fischer, E.G. Jenkins and J. Schot (eds.) (1996), *The Greening of Industry Resource Guide and Bibliography*, Washington, D.C.: Island Press.

Hart, S.L. and G. Ahuja (1996), Does it pay to be green? An empirical examination of the relationship between emission reduction and firm perfomance, *Business Strategy and the Environment* 5: 30-37.

Hertwich, E.G. (1997), *Eco-Efficiency and its Role in Industrial Transformation*. Working Paper. Vrije Universiteit, Amsterdam: Institute for Environmental Studies (IVM).

Higgins, T.E. (ed) (1995), *Pollution prevention handbook*, Lewis Publishers, Boca Raton.

Hinterberger, F. (1992), From Preference Theoretic "Paradoxes" to Market Failure? Paper prepared for a lecture of the Università di Firenze, Firenze 1992.

Hinterberger, F., N. Yavuz and A. Femia (1997), Some Thoughts on Sustainable Consumption, background paper, forthcoming as IHDP-IT no.7.

Hofkes, M.W. (1996). 'Modelling Sustainable Development: an economy-ecology integrated model', *Economic Modelling*, 13, pp. 333-353.

Den Hond, F., and P. Groenewegen (1993), Solving the Automobile Shredder Waste Problem: Cooperation Among Firms in the Automotive Industry. In: K. Fischer and J. Schot (eds.), *Environmental Strategies for Industry: International Perspectives on Research Needs and Policy Implications*. Washington, D.C.: Island Press. 1993.

Van den Hoed. R. (1997), An exploration of approaches towards sustainable innovation and their implications on the product development process, paper at the sixth Greening of Industry Network conference, Santa Barbara (CA), November 16-19, 1997.

Hull, R. (1994), Reaching for Sustainable Development, *Across the Board* 31 (April) 50.

Jaffe, A B , and R N. Stavins (1994), The energy-efficiency gap: What does it mean? *Energy Policy* 22 (10) 804-810.

Jendrosch, T. (1995), Gewohnheitstier Mensch. Verpackungen steuern das Konsumverhalten, *Verpackungsberater* (6).

Kapp, K.W. (1988), *Soziale Kosten der Marktwirtschaft*, Frankfurt a.M., Fischer-Taschenbuch-Verlag.

Kruijsen, J.H.J. (1997), Sustainable product innovation: The introduction of new technologies like solar cell technology, paper at the sixth Greening of Industry Network conference, Santa Barbara (CA), November 16-19, 1997.

Lenox, M. and J. Ehrenfeld (1997), Organizing for effective environmental design. *Business Strategy and the Environment* 6 (4): 187-196.

Lifset, R. (1997), Editorial, *Journal of Industrial Ecology* 1 (2), 1-2.

Lowe, E.A., Moran, S.R. and Holmes, D.B. (1996), *Fieldbook for the Development of Eco-Industrial Parks*, draft, Indigo Development, Oakland, CA.

Lowe, E.A., and J L. Warren (1996), *The Source of Value: An Executive Briefing and Sourcebook on Industrial Ecology*, Pacific Northwest National Laboratory PNNL-10943, Richland, Wa.

Luckenbach, H. (1982), Nachfrage des Haushalts. In: M.J. Beckmann (Ed.): *Handwörterbuch der Wirtschaftswissenschaften*, Wiesbaden: Gabler-Verlag, pp.300-314.

Lutzenhiser, L. (1993), Social and behavioral aspects of energy use, *Annual Review of Energy and the Environment* 18: 247-289.

Mauser, A. (1996), Milieumarketing: Milieu of marketing?, *Milieu* 11 (2) 69-80.

Meadows, D. et al. (1972), *The limits to growth: a report for the Club of Rome's project on the predicament of mankind*, Earth Island, London.

Meijkamp, R. (1997), Changing consumer needs by eco-efficient services: An empirical study on car sharing, paper at the sixth Greening of Industry Network conference, Santa Barbara (CA), November 16-19, 1997.

Michelsen, J. (1996), Organic farmers and conventional distribution systems: The recent expansion of the organic food market in Denmark, *American Journal of Alternative Agriculture* 11 (1) 18-24.

Miljøverndepartementet Norway (1995), Elements for an International Work Programme on Sustainable Production and Consumption. Conference on Sustainable Production and Consumption 06.-10.02.1995, Oslo Ministerial Roundtable 1995.

Molloy, M.T., and T. Ueki (1997), *Zero Emissions Industries: The Role of Consulting Engineering Firms*.

Morton, B., K. Green, S. New and C. Miller (1997), Negotiating environmental improvement: The emerging role of environmental supply chain management and NUS Services Ltd. In: ERP Environment (ed.), Conference Proceedings of the 1997 Business Strategy and the Environment Conference, Shipley: ERP Environment.

National Research Council (1997), *Environmentally significant consumption. Research directions*. (P C. Stern, T. Dietz, V.R. Ruttan, R.H. Socolow, and J.L. Sweeney (eds.)), Washington. National Academy Press, 1997.

Neuman, F. (1995), *The Incorporation of Environmental Elements in Strategic Decision-Making Processes in Industry Business-Government Interaction from a Corporate Perspective*. Rotterdam: Drukkerij Humanitas.

OECD (1991). Environmental Policy: how to apply economic instruments, OECD, Paris.

OECD (1997), Greener public purchasing. Issues Paper prepared by the OECD Secretariat for the International Conference on Greener Public Purchasing (Green Goods IV) in Biel-Bienne, Switzerland, 24th-26tn February 1997.

Oosterhuis, F., F. Rubik and G. Scholl (1996). Product policy in Europe: new environmental perspectives. Kluwer Academic Publishers, Dordrecht/Boston/London.

Opschoor, J.B. (1995), Ecospace and the Fall and Rise of Throughput Intensity, in: *Ecological Economics* 15 (2), 137-140.

Owens, J.W. (1997), Life-cycle assessment: Constraints on moving from inventory to impact assessment, *Journal of Industrial Ecology* 1 (1), 37-49.

Penz, R. (1991), *Ökonomie und Soziobiologie-ein methodischer Vergleich*, master thesis, University of Hamburg 1991.

Perrings C. (1987), *Economy and the Environment: a theoretical essay on interdependence of economic and environmental systems*. Cambridge University Press, Cambridge, 179pp.

Perrings, C. (1989), Environmental Bonds and Environmental Research in Innovative Activities, *Ecological Economics*, 1, pp. 95-115.

Perrings, C. (1994). Sustainable Livelihoods and Environmentally Sound Technology, *International Labour Review*, 133:3, pp. 305-326.

Perrings, C. and D.W. Pearce (1994). Threshold Effects and Incentives for the Conservation of Biodiversity, Environmental and Resource Economics, 4, pp. 13-28.

Powell, W.W., K.W. Koput and L. Smith-Doerr (1996). Interorganizational Networks of Learning in Biotechnology. *Administrative Science Quarterly* 41, 116-145.

Richards, D.J. (ed.) (1997), *The Industrial Green Game. Implications for environmental Design and Management*, Washington D.C., National Academy Press.

Røpke, I (1994), Sustainability and Structural Change. In: Université Panthéon - Sorbonne C3E/AFCET, *Models of Sustainable Development - Exclusive or Complementary Approaches of Sustainability?* International Symposium Paris 16.-18.03.1994, Vol.II, Paris 1994.

O'Rourke, D , L. Connelly, and C.P. Koshland (1996), Industrial Ecology: A Critical Review, *International Journal of Environment and Pollution* 6 (2/3): 89-112.

Ross, R.L. (1992), *Pollution Prevention: Homework and Design Problems for Engineering* Curricula. American Institute for Pollution Prevention, Washington, DC.

Ryall, C and S. Riley (1996), Appraisal of the selection criteria used in green investment funds. *Business Strategy and the Environment* 5: 231-241.

Ryan J.C. and Alan During (1997), *STUFF The Secret Lives of Everyday Things*, NEW Report No 4, Jan 1997, Northwest Environment Watch· Seattle, Washington.

Sachs, W. (1993), Die vier E's. Merkposten für einen maß-vollen Wirtschaftsstil. In: Politische Ökologie Special. Sept./Okt. 1993, S. 69-72.

Sachs, W. (ed.) (1994), *Der Planet als Patient Über die Widersprüche globaler Umweltpolitik*, Basel u.a.: Birkhäuser.

Sachs. W. (ed.) (1995), *The Political Anatomy of "Sustainable Development"*, Wuppertal: WIKUE, Wuppertal Papers No. 35.

Sachs, W. (1996), The Political Anatomy of "Sustainable Development", *Interculture* XXIX (1), 14-35.

Schaltegger, S. (1997), Economics of life cycle assessment: Inefficiency of the present approach, *Business Strategy and the Environment* 6, 1-8.

Van Scheppingen, Y. (1995). Milieugericht aanschaffingsbeleid bij provincies: case studie kantoormeubilair, Faculty of Economic Sciences and Econometry, Vrije Universiteit, Amsterdam, The Netherlands.

Scherhorn, G. (1993), Die Notwendigkeit der Selbstbestimmung, in: *Politische Ökologie* Special, Lebensstil oder Stilleben?, (Sept./Oct.) pp.6-9.

Scherhorn, G. (1997), Das Ganze der Güter. Unpublished Manuscript 1997.

Schulze, P.C. (ed.) (1996), *Engineering within Ecological Constraints*, Washington D.C., National Academy Press.

Selden, T.M. and D.S. Song (1994), Environmental Quality and Development: Is There a Kuzents Curve for Air Pollution Emissions? *Journal of Environmental Economics and Management*

Sheldon, C. (ed.) (1997), *ISO 14001 and Beyond. Environmental Systems in the real World.* Sheffield, Greenleaf.

P.S Sheng, D. Dornfeld and P. Worhach (1995), Integration Issues in Green Design and Manufacturing, *Manufacturing Review*, June.

Shu, L.H., D.R Wallace, W C. Flowers (1996), Probabilistic Methods in Life-Cycle Design, *Proceedings of the 1996 IEEE International Symposium Electronics and the Environment*, 7-12.

Shrivastava, P. (1994), Castrated Environment: Greening Organizational Studies. *Organisation Studies* 15 (5), 705-726

Stafford, E.R. and C.L. Hardy (1996), Green alliances: Strategic relations between businesses and environmental groups, *Business Horizons* (March-April) 50-59.

Steger, U. (1996), Organization and Human Resource Management for Environmental Management, In: Groenewegen et al. (eds.) *The Greening of Industry Resource Guide and Bibliography*, Island Press: Washington D.C.

Stern, P C. (1992), What psychology knows about energy conservation, *American Psychologist* 47 1224-1232.

Stern, P C. and E. Aronson (eds.) (1984), *Energy use: The human dimension*, New York: Freeman.

Stern, P.C and S. Oskamp (1987), Managing scarce environmental resources. In: D. Stokols, and I Altman (eds.), *Handbook of Environmental Psychology* Vol. 2, New York: Wiley, pp. 1043-1088.

Spangenberg, J.H. (ed.) (1996), *Towards Sustainable Europe. A Study for Friends of the Earth Europe*, Wuppertal-Brüssel: WIKUE.

Tol, R.S.J. (1996), *A Decision-Analytical Treatise of the Enhanced Greenhouse Effect*. Thesis Vrije Universiteit Amsterdam

ULS (1996), The Life Cycle of a Hamburger, to be found at http://cygnus-group.com/ULS/Current_ULS_Reports/No.13_MA96.html.

Vellinga, P, De Bruyn, S.M., Heintz, R., Anderberg, S., Davidson, O., Hinterberger, F., Taylor, M., Weaver, P., 1996. Industrial Transformation: Towards a Research Agenda for the Human Dimensions Programme on Global Change. Scoping Report, HDP, Institute of Environmental Studies, IVM W-96/6, IHDP-IT no 1.

Velthuijsen, J.W. (1995). Determinants of Investment in Energy Conservation, PhD-thesis, Groningen.

Veroutis, A.D. and Fava J.A. (1996), Framework for the Development of Metrics for Design for Environment (DFE) Assessment of Products. *Proceedings of the 1996 IEEE International Symposium on Electronics and Environment*, 13-18.

Wackernagel and Rees (1996), *Our Ecological Footprint: Reducing Human Impact on The Earth*, Gabriola Island, B.C.: New Society.

Van Weenen, J.C. (1997), Sustainable product development: Opportunities for developing countries, *UNEP Industry and Environment* (June) 14-18.

Wehrmeyer, W. and K.T. Parker (1995). Identification, analysis and relevance of environmental corporate cultures. *Business Strategy and the Environment* 4: 145-153.

Welch, E. (1997), The Organization Level of Analysis for Industrial Transformation, Background paper, IHDP-IT no.5

Weule, H. (1993), Life-Cycle Analysis: A Strategic Element for Future Products and Manufacturing Technologies, *Annals of the CIRP Vol 42/1/1993*, 181-184.

Young, S B., and W H. Vanderburg (1994), Applying Environmental Life-Cycle Analysis to Materials, *JOM* April, pp. 22-27

Yoshinori, K., Y. Moriguchi and H. Shimizu (1996), Creating an Inventory of Carbon Dioxide Emissions for Japan: comparison of two methods, *Ambio*, 25:4, pp 304-308.

Zurn, J and J Diener (1994), Ecological Assessment of Products and Processes -- Challenge and Opportunity, *Proc Recy' 94*, Erlangen, Germany.

Annex 1: Networks and organisations with a potential link to IHDP-IT

Table 1 provides an overview of various international networks and organisations that do relevant research in the area of Industrial Transformation. Without the aim of being exhaustive, it divides the organisations and networks around three clusters: (i) scientific research networks; (ii) intergovernmental organisations; (iii) international non-governmental organisations.

organisation	objectives	relevance to Industrial Transformation
networks		
LCANET	An European network which aims to be a platform for discussion on LCA research and development, and for identifying and describing state-of-the art of LCA methodology and applications to draw up a coherent strategic LCA research programme, including developments needed to employ LCA effectively as a policy support tool and as a 'driving force' for technological development in particular in the field of environmental technologies.	To stimulate and coordinate research on LCA which is an important subject in the physical exchanges between economy and the environment. It can provide support to policy making by the coordinating and standardising activities, f e. by the development of indicators for environmental impacts from economic activities
ConAccount	an European network which aims to be a platform for discussion on MFA research and development, and for initiating and supporting coordination of involved institutes	To stimulate and coordinate research on MFA which is an important subject in the physical exchanges between economy and the environment It can provide support to the integration of economic and physical modelling. It can provide support to policy making and environmental management.
WBCSD	to provide business leadership as a catalyst for change to sustainable development to provide eco-efficiency by encouraging high standards of environmental and resource management in business	to support and encourage industrial transformation in business
EBCSEF	an European Council which aims to be a platform for companies who see advantages in strengthening a sustainable energy-policy	To stimulate integrated resource planning, efficient use of energy in business

The Greening of Industry	a global network which aims to stimulate, coordinate and promote research of high quality and relevance to ensure that the activities of industry - including business, labour, consumers, government and others - are consistent with building a sustainable future	This network started building a research agenda on the theme's 'Transformation Towards Sustainable Development', 'Changing Consumption Patterns, Finance', 'Capital and Performance Indicators', 'Technological Breakthroughs'. One of its aims is to diminish the gasp between the academic community and the users of research by research policies
AFREPEN	a network in the Sub-Saharan Africa which aims to strengthen local research capacity and to harness it in the service of energy policy making and planning. It is a collective regional response to the wide-spread concern over the weak linkage between energy research and the formulation and implementation of energy policy in Sub-Saharan Africa.	To incorporate environmental concerns in energy policy and development
INES	a global network of engineers and scientists which aims to encourage and facilitate international communication among engineers and scientists to promote environmentally sound technologies, taking into account long-term effects to enhance the awareness of ethical principles among engineers and scientists	to promote the idea of industrial transformation by working on a responsible use of science and technology to promote collaborative and interdisciplinary research relating to the aim of IHDP-IT
EEPSEA	a Southeast Asian Network of academics and policy makers which aims to promote research in environmental and resource economics and on the use of economic instruments for environmental policy to make a significant contribution to regional environmental policy	to carry out research in environmental sciences, especially on the use of economic instruments for environmental policy to promote the IHDP-IT experience in Southeast Asia by providing regional and national institutions with an opportunity to learn from the experience of industrialised countries

IGO'S		
OECD - EPOC	to provide a forum for share views on, consider policy responses to and encourage cooperation in dealing with, major environmental issues and threats to promote the integration of environmental and economic policies, technological innovation and diffusion, and protection of environmental values and ecosystems to develop and promulgate environmental indicators and standardised, comparable sets of data and statistics	to investigate the policy options with respect to IT and to encourage cooperation in environmental policy to promote the diffusion of technological innovation
UNESCO	to promote collaboration through education, science culture and communication	to provide scientific knowledge and trained personnel to initiate science-based research programmes that are multidisciplinary, international and applied, f e. management of resources, technology development, integrated assessment of climate change, and the marine environment public information
UNEP	to facilitate international cooperation in environmental matters environmental management with respect to industry and the environment to promote the acquisition, assessment and exchange of environmental knowledge	to support measures with respect to environmental education and public information environmental management with respect to industry
UNIDO	to promote and accelerate industrial development in developing countries	to integrate the idea of sustainable development in industrial development, especially in developing countries

The World Bank	to help raise standards of living in developing countries to provide capital and promote private foreign investment for productive purposes to identify the more useful and urgent projects required to support economic and social development	to conduct research in the areas of energy and industry to integrate environmental considerations in developing industrial activities in developing countries

IPCC	to asses available scientific information on climate change to assess the environmental and socio-economic impacts of climate change to formulate response strategies	policy making, research at the integrated assessment on climate change
WCRP	to enhance and coordinate research on global climate change	to provide information by research which can help understand the human impact on and dimensions of global climate change
NGO's:		
EEB	to affect EC environmental policy and projects to promote an equitable and sustainable life style to promote protection and conservation of the environment and better use of human resources public awareness	to affect the environmental policy in the areas transportation, energy and pollution control.
ICC	promoting trade, investment and the free market investment to represent business and defend interests of private business to standardise rules and practices for international business	to stimulate the idea of transformation in international business world
IOCU	to protect and promote consumers rights and interests	to promote the awareness of sustainable consumption
ISES,	to promote the utilisation of solar energy	to stimulate scientific research 2nd law thermodynamics to exchange information of experience
SID	to promote international dialogue, understanding and cooperation for social and economic development that is equitable and sustainable	to stimulate scientific research, affecting policy to promote IHDP-IT, mobilise of national and international support for IHDP-IT

Table a 1

LCANET	European Network for strategic Life-Cycle Assessment Research and Development
ConAccount	Coordination of Regional and National Material Flow Accounting for Environmental Sustainability
WBCSD	World Business Council of Sustainable Development
EBCSEF	European Business Council for a sustainable Energy Future
The Greening of Ind.	
AFREPEN	African energy Policy and Research Network
INES	International Network of engineers and Scientists for Global Responsibility
EEPSEA	Economy and Environment Program for Southeast Asia
OECD-EPOC	Organization for Economic Co-operation and Development -Environment Policy Committee
UNESCO	United Nations Educational Scientific and Cultural Organization
UNEP	United Nations Environment Programme
UNIDO	United Nations Industrial Development Organization
The World Bank	
IPCC	Intergovernmental Panel on Climate Change
WCRP	World Climate Research Programme
EEB	European Environmental Bureau
ICC	International Chamber of Commerce
IOCU	International Organization of Consumer Unions
ISES	International Solar Energy Society
SID	Society for International Development

Annex 2: Indicators

In the above sections, it has been pointed out that empirical work is being hampered by a lack of appropriate indicators for environmental impacts from economic activities[5] or the development towards a common environmental metric.

Indicator development has been taken place along two different lines. The first approach is the monetarisation of environmental impacts, which has frequently been done in the area of *integrated assessment* The question whether this approach can be valuable for the other areas of IT too is not clear and should be investigated in more detail. For example, the fact that lower management in companies is still to be judged by economic efficiency criteria implies that there may be scope for deducting environmental losses from these value criteria. Similar remarks have been made in the area of Green National Accounting (cf. Hueting, CBS the Netherlands; Repetto, World Resources Institute).

Yet there are a number of technical and ethical problems at stake. From an ethical perspective it is not always feasible or desirable to convert all environmental benefits and costs into dollar values. Some benefits and costs may be difficult to identify because of a lack of knowledge about ecosystems. Driver and Burch (1988) argue that information could be lost in the process of translating the diverse benefits of a resource into a single monetary value. Other people argue that the benefit to society of environmental resources is too complex to be captured by a single dollar value and to attempt to do so is to trivialise the importance of the environment (Cameron 1992, p.159) Other benefits and costs may be controversial, such as the value of life, and tend not to be measured in dollars[6]. Moreover, valuing environmental impacts implies that only anthropocentric values are taken into account and that future generations are only presented through the altruism of current generations.

Another approach is therefore the 'physical indicator approach'. Here no attempt is being made to use money as the common aggregation principle. To a certain extent, different type of emissions can be added in order to assess the environmental impacts in certain relevant fields, such as acidification, nutrification, enhanced greenhouse effect or the depletion of the ozone layer (Aadriaanse, 1993). Attempts have been made to proceed one step further, to add these environmental impacts into one single indicator for emissions, based f.e. on

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5 See the advanced, although still controversial debate on SD-indicators in Europe/OECD: Adriaanse 1993, Opschoor/Reinders 1991, Kuik/Verbruggen 1991, UN 1991, Weterings/Opschoor 1992, Rennings 1994, Bringezu 1995, Opschoor/Costanza 1995, Spangenberg/Schmidt-Bleek 1995; for its potential and effective use in Developing Countries see Fürst 1996.

6 Certain conventions about equity and morality are assumed in an economic analysis. For example, most economic studies assume that the values given to a resource should be limited by people's ability to pay for them, and that the current distribution of wealth is acceptable. Some people's economic votes therefore have a higher value than others because a rich person is more likely to be willing to pay more to protect (or degrade) an environment than a poor person. In consequence, some individual's preferences count a great deal and others' hardly count at all.

expert-views or the concept of 'environmental utilisation space', but the question whether these approaches are useful are still under debate (cf. VROM, 1994). For indicators on materials and energy flows, different aggregation schemes have been proposed by the Wuppertal Institute which aggregate material flows by weight7, or by aggregating on 'net energy'8 or 'entropy'9.

The urgency for measuring environmental impacts have also been stressed from the business perspective. With LCAs the lack of a common indicator implies that as long as the emissions contained in the inventories cannot be aggregated and compared, the most polluting inputs or production steps cannot be identified. Out of this need and the dissatisfaction with the simple aggregation of the masses of emissions, as practised with TRI, many different and often ad hoc methods for impact evaluation have been developed. Davis *et al.* (1994) review many of the methods used in the United States, others include those of SRRP (1993) and Graedel *et al.* (1995). Sage (1993) reviews and applies a number of the methods used in Europe. The most sophisticated tools have been developed for the assessment of life cycle inventories and toxics release inventories. SETAC has provided a general outline of how to aggregate different emissions that cause different environmental problems ranging from global warming to eco-toxicity (Fava *et al.*, 1993). The SETAC method aggregates emissions into different impact categories, such as global warming, and eutrophication using equivalency potentials such as CO_2 equivalents and N_2O_5 equivalents. SETAC has not yet developed a procedure to aggregate the equivalency potentials to a single impact score, but a Dutch consulting firm has proceeded to this step (Goedkoop 1995). Competing impact assessment methods include the sustainable process index (Narodoslawsky and Krotscheck, 1995), the environmental priority system (Steen and Ryding, 1991), and the Swiss eco-points (Ahbe et al. 1990). Hertwich *et al.* (1997) provides a systematic analysis of these quantitative impact assessment methods.

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7 This is the Wupperthal Institute-approach which draws its dematerialisation proposal (reduction of material throughput by a factor 10 in the industrialized countries) on an one dimensional indicator - called MIPS=Material Intensity per Service Unit - by measuring with this the total primary and intermediate input of biotic and abiotic resources, energy carriers, materials and semi-finished parts during the total life-cycle production and consumption process of a product with service function (i.e. from the moment of using the nature as source until the moment of utilizing the ecosystem as sink, including the so-called "ecological rucksacks"). See for this indicator and the corresponding policy approach of eco-efficiency/-sufficiency in order to achieve the aimed dematerialisation of the economy in Germany and other countries with industrial metabolism features: Schmidt-Bleek 1993, Bringezu 1995, BUND/MISEREOR 1996 and -more recently- the interesting analytical foundation based on input-output-analysis by Femia/Hinterberger/Luks 1996.

8 It has often been proposed that energy stocks and flows are the key determinants of ecological systems (cf. Odum). Formal analysis on this aggregation scheme have been provided by f.e. Chapman, 1974 and Hannon, 1975.

9 See the overview of Ayres and Schmidt-Bleek, 1993 on various aggregation schemes.

4. Annex 3: Technological change

The importance of technological change for all parts of the research field in IT is highlighted by the observation that there is some evidence that almost all of the reduced pressure on the environment in developed economics has been brought about by improvements in technology of production.

In economics, the area of technological change has recently received a good deal of attention where theories often can be traced back to the original work of the Austrian economist Schumpeter. Schumpeter explained aggregated fluctuations (business cycles) by the activities of entrepreneurs in time, that is by innovation flows. In other words: the sources of endogenous economic changes are to be found in the activities of the entrepreneurs. This line of thought has been taken up by several authors (Alchian, 1950; Friedman, 1953; Becker, 1962, 1976, Loasby, 1983; Metcalfe, 1989; Nelson and Winter, 1982; Dosi et al., 1988) who developed theories about the performance of industries and firms in the competitive and innovative struggle (Witt, 1993 xiv). They are connected closer to Darwinian thought than Schumpeter was.

Most analysis of technological change takes one of three perspectives: the processes of technological change and its relationship with strategic management (Teece, Klein and Rosenberg, Tornatsky); organisational characteristics that determine the relative innovativeness of firms (Daft, 1989; Adler, 1989); and the interplay of technological change and economics (Chesnai, 1986; Dosi, 1988; Freeman, 1982).

It is suggested here that greater efforts by all three of these research trajectories are needed in order to make theories of technological change compatible with current thinking about sustainability. For example, while there is some indication that green innovation (such as input substitution, process technology changes, or interfirm linkages to close material loops) is linked to market forces, other organisation characteristics such as structure, size, information control systems, boundary spanning networks, leadership decision making and corporate culture may be as or more important determining factors. It appears from the management and decision making literature reviewed above, that while economic considerations are important to environmental decision making, other factors such as leadership, persuasiveness, peer pressure, internal power relationships, and external policy factors often override economic drivers. What are the internal trade-offs made by firms within the context of adoption and innovation of technology? How high must policy incentives or government pressure be to change organisational motivations toward substantive incorporation of ecological imperatives into R&D processes. Does green innovation follow similar market pull and technology push dynamics that have been so

much a part of technological change, productivity, and competitiveness discussions of the past?

With respect to the techno-economic perspective of technological change, Rene Kemp's work provides an initial attempt to begin an environment-saving technological change framework of analysis and to test it empirically with case studies. However, the author's review of future research needs also points to the underlying lack of existing work on the subject. He outlines three areas which require attention: (1) the theoretical framework itself; (2) the relationship between market structure and innovation in and diffusion of cleaner technologies; (3) corporate attitudes toward clean technologies and their use of different strategies to achieve competitiveness. Others, such as Schot, have also provided some analysis of technological change (Schot, 1992).

Second order effects, such as the so-called rebound effects are important in this context too. Khazzoum (1987) describes the rebound effect as "a feedback from the engineering to the behavioural sector". In brief, it describes the process whereby a reduction in energy input leads to a reduction in the cost of the service provided. This stimulates demand for the service, increasing output and hence increasing the energy input.

An example of the management perspective is provided by Ashford who examines the range of technological responses to environmental problems by industrial firms. While he does not test his model empirically, he does develop a framework from which he argues that "the key to success in pollution prevention is to influence managerial knowledge or and managerial attitudes toward both technological change and environmental concerns (Ashford, 1993). Lanjow and Mody examine the factors influencing innovation and the international diffusion of environmentally responsive technology. They find possible connections between innovation and regulation (Lanjow & Mody, 1996). This seems to indicate some empirical support for Porter's hypotheses that regulation pushes innovation (Porter, 1990). Milliman and Prince have also examined the process of technological change with respect to pollution control and its relation to a variety of policy incentives to determine how different policies affect firm incentive structures (Milliman & Prince, 1989). Findings indicate that economic instruments provide the highest incentives for pollution control innovation. Steger also takes an innovation perspective when he asks the question, "What are the relevant features of corporate culture promoting environmental responsiveness?, What are the appropriate incentives and external leverage?; and what internal structures best promote organisational learning and innovation in the ecological context (Steger, 1996)?

Industrial Ecology: Some Directions for Research

May 1997

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Foreword

The recent diffusion of the term "industrial ecology" stems from its use by physicist Robert Frosch in a paper on environmentally favorable strategies for manufacturing co-authored with Nicholas Gallopolous published in September 1989 in *Scientific American*. Frosch embraced the concept of "industrial metabolism" which Robert Ayres has developed to organize thinking about the massive, systematic transformations of materials in modern economies. Industrial metabolism as well as dematerialization (the diminishing amount of material required for a good or service) had been explored at an August 1988 workshop of the National Academy of Engineering chaired by Frosch (Ausubel and Sladovich, 1988). Frosch sought a term that conveyed not only the sense of transformation but also the networks of actors doing the producing and consuming – or disposal – of materials and associated energy.

The new term resonated. The National Academy of Sciences, in association with the AT&T Corporation, convened a "Colloquium on Industrial Ecology" chaired by Kumar Patel in May of 1991 to consider the subject more fully. The Colloquium addressed optimization of the total materials cycle, from virgin to finished material, including components, products, waste products, and ultimate disposal (PNAS 89(3), 793-884, 1992).

During the past few years, a growing number of researchers as well as practicing engineers and managers have been attracted to "industrial ecology." The term appears to offer a framework within which to improve knowledge and decisions about materials use, waste reduction, and pollution prevention. Some dozen workshops, many organized by NAE, have explicitly addressed aspects of industrial ecology. These include applicability in selected

manufacturing sectors, applicability in services industries, environmentally symbiotic co-location of industries, comparative experiences in different nations, relationship to global environmental problems, and performance measures. Braden Allenby and Thomas Graedel codified much of the early knowledge in a 1995 textbook. Several universities and other research institutions now have courses or programs in industrial ecology. The U.S. government's National Environmental Technology Strategy endorsed the concept. A *Journal of Industrial Ecology* has been established as well as a fellowship program. Swiss journalist Suren Erkman (serkman@mail.vtx.ch) has built a database of relevant publications containing over one thousand items. Popular articles have appeared in newspapers and magazines, and even a sociological review (O'Rourke et al, 1996) .

Of course, no subject is wholly new, and antecedents have been traced. Importantly, individuals with similar and related interests in numerous countries have joined the discussion.

In this period of maturation, a group of us who have participated in the growth of industrial ecology (calling ourselves the Vishnu Group, for the Hindu deity embodying preservation) agreed in December of 1995 that it could be useful to outline research directions for the field. Notwithstanding the existence of much research planning in fields of environmental science and technology, we found little language that addressed the needs we see. The interest of the US Department of Energy, and Lawrence Livermore National Laboratory in particular, to learn more about industrial ecology provided the occasion and generated the needed financial support. The Program for the Human Environment at The Rockefeller University agreed to serve

as the hub for the activity. We met twice as a group and interacted extensively in smaller meetings and through telecommunications. Iddo Wernick took the lead in drafting the report.

We speak about issues and problems rather than disciplines. We believe people with diverse backgrounds, skills, and specialized knowledge from physical and life sciences, engineering, and social sciences as well as industrial practice will all contribute to the advancement of industrial ecology. Many of the problems will benefit from analysis by teams combining fields of expertise. Universities, government laboratories, and both for-profit and not-for-profit private sector research groups may all find areas appropriate for their labors.

We are well aware that researchers are conducting a considerable amount of high-quality relevant work in Austria, Canada, Denmark, Netherlands, Japan, Germany, Italy, Switzerland and other countries. Although some of this is represented in the bibliography, we have not had the time or means to carry out a systematic global survey. We have tried to identify directions that soundly reflect the mix of industries and environmental issues that characterize the United States. We have yet to estimate the costs in human effort or dollars of the research envisioned. An obvious next step is to make such an assessment and to search for bargains.

We are grateful to numerous individuals for materials, comments, and suggestions. These include Stefan Anderberg (IIASA), David Berry (President's Council on Environmental Quality), Raymond Cote (Dalhousie), Richard Dennison (Environmental Defense Fund), Peter Eisenberger (Columbia University), Suren Erkman (Geneva), Gregory Eyring (formerly US Office of Technology Assessment), Peter Ince (USDA Forest Service), Greg Keoleian (Michigan), Catherine Koshland (U. of California, Berkeley), Roberto Galli (Milan), Grecia

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Jesse H. Ausubel
Director, Program for the Human Environment

PREFACE

Among the goals of industry must be the preservation and enhancement of the environment. Anticipating a world with more industrial activity, we must find ways to make large improvements in the totality of industrial interactions with the environment. Each corporation may see incentives to better its individual environmental performance. Consideration of the collective performance of an economy is necessarily a public function. A broad view is needed, for example, to encourage waste minimization as a property of the industrial system even when it is not completely a property of an individual process, plant, or industry. Much of the research and understanding that underlie such a system must also be of a public and open character.

The energy sector is the largest handler of materials in the economy. Current annual global emissions of carbon, our main fuel, are about 6 billion tons, or more than 1,000 kilograms per person on the planet. In comparison, the global steel industry annually produces about 700 million tons, or about 120 kilograms per person. Energy, of course, also interacts with every other industry, ranging from cars and chemicals to paper and electronics. For these and other urgent reasons, the energy sector and the US Department of Energy have thus had a long-standing and growing interest in how industry can be more safely and cleanly embedded in the environment.

The commitment of the US government to more effective, long-term approaches to environmental quality has been reiterated and elaborated in such recent reports as Technology for a Sustainable Future (National Science and Technology Council, 1994) and the 1996 report of

the President's Commission on Sustainable Development. The 1995 report on Alternative Futures for the Department of Energy National Laboratories prepared by the Advisory Board of the Secretary of Energy (Galvin Committee) pointed out that the laboratories have areas of demonstrated expertise that could provide the basis for an expanded mission in environmental research and technology development.

In the spirit of these deliberations, the Office of Energy and Environmental Systems of the Lawrence Livermore National Laboratory concluded it would be useful to learn more about the promising directions for research in the emerging field of industrial ecology. We received encouragement in this regard from our colleagues elsewhere in the Department of Energy as well as from other federal mission agencies and the White House. We hope that this report will now helpfully stimulate not only the performers and sponsors of research within the DOE, but thoughout the government and in industry and academia as well.

Phrases such as "sustainable development" will remain little more than slogans unless disciplines such as industrial ecology can provide operational concepts that improve both the economy and the environment.

Braden R. Allenby
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I. INTRODUCTION

The Goal and the Role

If humanity grows in number and wealth yet tries to meet its desires for goods and services only in the same ways we do today, we will surely suffer from a badly polluted environment. If technology and the organization of economic activity stagnate, pollution will multiply. Fortunately, the historical record shows some hope that people can change their ways and lessen their impact on the environment while wealth increases. In fact, wealth pays for the innovations that can lessen our impact.

The role of Industrial Ecology (IE) is to learn about the levers for lightening the impact on the environment of each person and each dollar of economic activity. This report sets out how diverse engineers, scientists, and investigators and practitioners in other fields can learn where some of the levers are, how they work, and how they might be improved and used.

IE accepts as givens population and income. Industrial ecologists listen to demographers, experts in economic development, and others for definition of the dimensions of the challenge to be addressed. For example, if the US population rises from its present level of about 260 million to 400 million in the year 2100 and the economy doubles per capita roughly every 30 years, as it has since the year 1800 in the industrialized countries, the United States would have more than 12 times today's emissions, other things being equal. To enhance environmental quality over the next century in this scenario, the annual cleaning of the US economy needs to exceed 2.5 percent. It is the job of American industrial ecologists to exceed 2.5 percent.

To do our job of minimizing waste and thus harmful exposures, various forms of environmental disturbance, and inefficiency, industrial ecologists examine such factors as

choices of raw material, the intensity and efficiency of use of materials, and fates of materials. We focus on technical aspects of a particular set of links in the chain of economic activity, while recognizing the value of other social and behavioral approaches to improving the human environment as well. We believe research is a gilt-edged investment to fulfill the stated contract of industrial ecology.

A recognizable body of IE research has emerged in recent years. This includes comprehensive accounts of the flow of selected materials in the economy, descriptions of the environmental dimensions of industrial systems as distinct from their artifacts, means for analysis and design of environmentally benign systems as well as artifacts, and alternatives to disposal for various wastes.

This report categorizes some of the main directions for research for IE and specifies avenues of inquiry. To view IE, we first talk about its fundamental means, the candidate ways for lessening impacts. These include industrial systems conceived to approach zero emissions, the substitution of materials with superior environmental performance, "dematerialization" or reduced intensity of use of materials, and reconceptualization of the economy to emphasize functions, i.e., services over goods. Then we discuss the measures for discovering and quantifying progress. These include materials accounting frameworks, analyses of the life cycles of products, indicators, and historical and comparative studies to discover dynamics and tendencies. Subsequently we discuss research aimed at implementation of IE, first through the technical means to advance the material basis of the economy and then through institutional means, including informational, financial, regulatory, and legal, as well as regional strategies.

Works listed in the accompanying bibliography provide background and examples for each section.

Before turning to the practical core of our report, we comment briefly on the conceptual premise of industrial ecology, which itself merits research.

How Industrial Ecology Got Its Name

The name or phrase "industrial ecology" *prima facie* implies that models of non-human biological systems and their interactions in nature are instructive for industrial systems that we design and operate. What makes the biological model attractive? Foremost is the cleverness with which evolution has developed things to live off the bodies and wastes of one another. Additionally, during the past few decades ecologists appear to have developed some skill at understanding systems by analyzing or depicting their flows and cycles of materials and energy.

A more problematic question is efficiency. Ecosystems are not necessarily exemplars of efficiency. Even the most efficient ecosystem, say, a corn field, captures only about 5 percent of solar energy as the product of photosynthate. In the summertime, most of the energy overheats the plant or evaporates water that the plant needs to keep turgid. In a mature, stagnating forest (likely to please the eyes of a naturalist), decay returns the CO_2 in the photosynthate to the air, making the efficiency zero.

The proposition that industrial systems may be beneficially viewed as ecosystems merits critical probing. An early step is simply to articulate a vocabulary matching or accommodating different morphologies. Research should also explore the applicability to industry of ecology's concepts (adaptive pathways, food webs, limiting factors, energy and material budgets) and rules

(e.g., Cope's rule that increase in body size confers adaptive advantages, the least work principle). Also valuable might be an exploration of the properties that favor ecosystem resilience, and what these suggest for the design of industrial networks. For an introduction to the ecological analogy, see Graedel, T.E., 1996, On the Concept of Industrial Ecology, *Annual Review of Energy and Environment,* Volume 21; Allenby, B.R. and Cooper, W.E., 1994, Understanding Industrial Ecology from a Biological Systems Perspective, *Total Quality Environmental Management*, Spring 1994 pp. 343-354.

Over the long run, industrial ecology is a good name for the discipline we have in mind only if there is merit to, and insight from, the analogy, not because it connotes an environmentally friendly industry.

II. MEANS AND MEASURES

Candidates for Lessening Impacts

Zero Emission Systems

An overarching goal of IE is the establishment of an industrial system that cycles virtually all of the materials it uses and releases a minimal amount of waste to the environment. Theoretically, the developmental path to such an end state follows an orderly progression from what Allenby and Graedel call Type I, II, and III systems. Type I systems require a high throughput of energy and materials to function and exhibit little or no resource recovery. Type II systems represent a transitional stage where resource recovery becomes more integral to the workings of the system but do not satisfy its requirements for resources. The final stage, the Type III system, cycles all of the material outputs of production, though still relying on external energy inputs.

Research is needed to elaborate this vision of future industrial ecosystems that are looped rather than leaky and to develop dynamic scenarios of how to achieve it technologically, at various levels of economic activity and population. Achieving it means that part of IE is a systematic search for leverage.

The research must especially consider basic industries (such as those providing energy, food, shelter, transport, as well as services) that currently rely on the vast mobilization of material resources. Fundamentally, this effort involves the search for alternatives to present systems that incorporate technologies that limit initial resource requirements and generate and recover usable waste products. The most developed thinking about zero emissions has occurred in the context of energy systems, particularly in relation to the use of hydrogen as an energy

carrier. Recent attention has focused on electric cars as zero-emission vehicles and the larger question of the energy and material system in which the vehicles are embedded. Classic studies about hydrogen energy might be revisited and extended in the context of industrial ecology (Gregory, D.P., 1973, A hydrogen-energy system, L21173, American Gas Association, Washington DC). See Hafele, W., Barnert H., Messner, S., Strubegger, M., and Anderer, J., 1986, Novel Integrated Energy Systems: The case of zero emissions, pp. 171-193 in Clark, W.C. and Munns, R.E., eds., *Sustainable Development of the Biosphere*, Cambridge University Press, Cambridge, U.K.

Material Substitution

The goal of minimizing waste may be reached by the leap of using a wholly new material for a purpose rather than refining the processing of an old material. The new material should perform the function longer, be processed less wastefully, or be acquired with less waste. Widespread examples of materials substitution include metals for wood, aluminum for steel, and high carbon steel for other steels, and, more specifically, steel for rayon in tires and plastics for glass in beverage containers. Historically, many of the substitutions have been alloyed blessings, bringing new environmental problems as well as reducing old ones.

Research is needed to understand the evolving consumption levels and applications of the materials used to provide various economic functions, the physical and chemical properties (e.g., strength-to-weight ratio, corrosibility, toughness, thermal stability) that motivate the selection of one material over another, and the time scales necessary for the substitution of materials by superior competitors. The purpose of the research would be to identify the materials for which

we should most actively seek substitutes, the most promising alternatives, and the feasible time scales to effect substitution.

Dematerialization

Materials substitution is considered a principal factor in the theory of dematerialization. The theory asserts that as a nation becomes more affluent the mass of materials required to satisfy new or growing economic functions diminishes over time. The complementary concept of decarbonization, or the diminishing mass of carbon released per unit of energy production over time, is both more readily examined and has been amply demonstrated by researchers over the past two decades. For materials in general, several forms of innovation (more efficient recovery of minerals and metals from crude ores, imbuing materials with improved properties per unit mass; and better societal mechanisms for handling and reusing wastes) drive this purported phenomenon. Dematerialization is advantageous only if using less stuff accompanies or at least leaves unchanged lifetime, waste in processing, and waste in acquistion.

Despite the collection of multiple anecdotes to support the dematerialization hypothesis few studies have offered a systematic approach for testing it. Research is needed to both advance the theoretical framework for dematerialization and for identifying the means to validate it. For a presentation of the dematerialization hypothesis see Bernardini, O., and Galli, R., Dematerialization: Long Term Trends in the Intensity of Use of Materials and Energy, *Futures*, May 1993, pp. 431-48 (1993); See also Wernick, I.K., Herman, R., Govind, S., Ausubel, J.H., Materialization and Dematerialization: Measures and Trends, *Daedalus* 125(3):171-198.

Functionality Economy

An interoffice envelope can carry a new address and a new message, but carries many messages before the space for addresses is filled. One cathode ray tube or flat screen display can convey countless messages. From the viewpoint of IE, products represent a means for serving a particular function to the consumer. A shift in the prevalent attitude of managers, engineers, and public officials from viewing products as endpoints in themselves to seeing them as providing functions to end users could translate to wholesale reductions in national resource use and diminished waste streams.

For example, in this view one does not purchase an automobile but rather the function of transporting passengers and goods. As a result the manufacturer does not relinquish prime ownership of the vehicle at any time and must reassume possession at the end of the vehicle's useful life. This arrangement provides strong incentive to design the vehicle for extended useful life and maximum recoverable value after use. The proliferation of cheap telephones with short service lives provides a counter example where the end of a decades-long leasing arrangement for telephones has led to a new source of municipal solid waste and significantly increased the number of devices manufactured.

Due to the incentive to extend product life the planned obsolescence of products could itself become obsolete as the acquisition of a physical object would be subordinate to the purchase of the function it provides. Research is needed to examine the most promising industries in the economy where this view may yield fruitful results. Further research is then needed to design the economic, regulatory, and legal systems necessary to introduce such 'function as product' arrangements in the broader marketplace. The functionality economy

substantially redefines industrial activity, with particularly profound implications for manufacturing concerns. For an introduction to this topic see Stahel W. R., The Utilization-Focused Service Economy: Efficiency and Product-Life Extension, pp. 178-190 in *The Greening of Industrial Ecosystems*, B.R. Allenby and D.J. Richards, eds, 1994.

Methods for Discovering and Measuring Progress

Three analytical methods for finding leverage suggest themselves. The first maps the flow of a material such as lead through the nation's industry, a sector, and even an individual firm. This mapping resembles the analysis of the dollars or energy in an economy. The second follows a product through its life from assembly to junk yard (and beyond) and encompasses all the material in it. The third examines the course of, say, iron per dollar of GDP, to learn whether a society is approaching or retreating from IE's goal of lightening the environmental impact per person and per dollar.

Materials Flow and Balance Analysis

Understanding the structure and environmental effects of industrial systems requires a knowledge of their anatomy and physiology. Materials flow studies reveal structure, and webs of economic and material relationships among actors, in the industrial system as they map the flow of natural resources into processing and manufacturing industries and the fate of products and wastes exiting them. The object for study can be the mass of individual chemical elements, compounds, or entire classes of materials. The framework for such studies include individual facilities, whole industrial sectors, and geographic regions.

Currently much of the challenge in constructing materials flow accounts at all levels lies in the absence of organized data sets. In many cases the data are collected but effort is necessary to compile data from many sources into a useful form. In other cases the data simply do not exist.

Much effort has been made to detail the mass flows of carbon, nitrogen, sulfur, and phosphorus. Their role in the biogeochemical functioning of the planet attaches importance to changes in their concentration in environmental media and their biological availability. In addition to the enormous volume of these elements cycling in the biosphere, their environmental significance depends strongly on their chemical form. Despite decades of effort researchers have yet to arrive at a full understanding of the natural sources and sinks of these elements and the precise impact of anthropogenic perturbations to the cycle. Still, IE can learn from our understanding of the global sources and sink., including anthropogenic ones, for these elements, and their transport through environmental media, and seek to contribute practical opportunities for reducing human perturbations to the global system. For example, attractive ideas need to be developed for the industrial recapture of carbon dioxide.

For less ubiquitous elements that carry with them a clearly harmful environmental impact, however, the task of circumscribing the amounts mobilized by natural and human activity and examining their metabolism in the industrial system is more feasible. Mass balance studies must consider the manifold chemical transformations that elements, such as chlorine (1991 US production 10.4 Million Metric Tons (MMT)), undergo in industry. *Figure 1* shows a first-order analysis of the industrial metabolism of elemental chlorine in Western Europe in 1992

The complex structure of use of this element in industry highlights the different possible levels of details for mass balance studies.

If the goal is to minimize toxic waste, not just waste, surely the form of the waste ranks with all the other concepts. For example, if we are making poisonous phosgene ($COCl_2$), it matters much whether we emit phosgene or CO_2 and NaCl. De-toxifying waste is a pre-eminent engineering task.

Mass flows for elements consumed in far smaller quantities than chlorine, such as cadmium (1993 US consumption 3.1 kMT), can be described more fully due to their smaller volume and relatively limited number of industrial applications. Mass flow analyses for arsenic, cadmium, chromium, cobalt, manganese, mercury, salt, tungsten, vanadium, and zinc are available from the Office of Minerals Information at the US Geological Survey (formerly the Branch of Materials, Division of Mineral Commodities at the US Bureau of Mines) located in Reston, Virginia. These analyses vary in their level of detail and in their environmental, as opposed to economic, relevance. At a minimum however, the studies contain valuable data and provide an excellent base for future studies.

Scanning the periodic table of elements brings into focus the most promising candidates for the development of detailed mass-balance accounts. Toxic elements such as those identified on the Agency for Toxic Substances and Disease Registry (ATSDR) as priority substances for toxic profiles provide some initial guidance in selecting elements for mass-balance accounts. (An element's LD_{50}, the dosage that will, on average, kill 50% of a group of experimental animals provides another possible method for ranking elements by toxicity and is regularly used

as a basic toxicity indicator for hazardous chemicals.) Toxic elements enter the environment through industrial activities that deliberately use them for their unique properties and from the processing and thermal treatment of ore and mineral bodies where they occur as trace elements. These are of course prime candidates for an engineer to find substitutions. Other elements and basic minerals to be included on the priority list are those involving large materials and waste flows even if they themselves do not present any acute toxic threat. Table 1 lists some representative metallic elements for which mass balance accounts are most needed along with some of the criteria for their determination.

Consideration of these elements begins with the amount the nations consumes, goes on to how much escapes from processing, and ends with whether the escape matters, the toxicity of the element.

Table 1

Element	1994 US Consumption (1,000 metric tons)	1992 Toxics Release Inventory (TRI) Production-related Waste (1,000 metric tons)*	ATSDR Priority group listing
Lead	1500	620.752	1
Nickel	131	68.792	1
Arsenic	19.4	6.209	1
Beryllium	0.2	0.0063	1
Cadmium	2.0	7.069	1
Chromium	387	125.184	1
Mercury	0.6	0.927	2
Zinc	1350	260.346	2
Selenium	0.5	0.364	2
Silver	4	2.733	3
Copper	2800	534.298	3
Thallium	0.8	0.038	4

* Wastes values for elements and their compounds

For relatively well understood systems, such as single industrial facilities, mass-balance studies rely on the simple, though underutilized, law of conservation of mass. By using available data establishing the mass of either inputs or outputs, the conservation law along with other process information (e.g., chemical reaction rates) allows researchers to construct the other side of the equation. For energy consumption, knowledge of the energy diet of the system under question allows researchers to gauge the amount of energy used for plant operation, embedded in manufactured products, and dissipated as heat.

Another vantage point for assessing materials flows is via industrial sectors. *Figure 1* shows a 'spaghetti diagram' indicating both the magnitude and direction of the metals flows for a portion of the non-ferrous metals sector in New England. The data used for the figure are drawn from direct interviews and site visits, official state and federal reports, and telephone questionnaires. Notwithstanding the extensive time and human effort expended, the study was limited both geographically and in the number of facilities examined, demonstrating the difficulty involved in obtaining reliable and accurate waste data. The study also underscores the fact that, when viewed in absolute terms, even small loss rates (around 1% for copper and 5% for lead) translate to significant environmental releases and suggest the need for even more scrutiny when examining larger scale flows where small differences in calculated efficiency can hide or reveal substantial volumes of waste. See Frosch, R.A., Clark, W.C., Crawford, J., Sagar, A., Tschang, T.T. and Weber, A., 1996, The Industrial Ecology of Metals: A reconnaissance, available from the John F. Kennedy School of Government, Harvard University, Cambridge, MA.

For more comprehensive, if less detailed, studies of entire sectors, IE can draw on an analytic base established by United States government departments and agencies. The US Department of Energy's "Industries of the Future" program focuses on the fundamental materials processing industries of petroleum refining, chemicals, pulp and paper, aluminum and glass, and steel. In addition to being industries with large resource requirements and waste outputs, these industries are considered basic to future national economic health and competitiveness. The US Environmental Protection Agency's (USEPA) "Common Sense" program looks at automobile manufacturing, computers and electronics, iron and steel, petroleum refining, and the printing industries. In addition to environmental concerns, economics and politics figure prominently in driving the selection of industries for these government programs. Table 2 lists a preliminary selection of industrial sectors (arranged by SIC code), as well as some criteria for determining their priority for IE research.

Consideration of these sectors begins with the amount the nations consumes, goes on to how much escapes from processing, and ends with whether the escape matters, the toxicity of the element.

Table 2

Sector	Two Digit Standard Industrial Classification (SIC) Code	1990 Domestic Production est. (10^6 MT)	1985* Non-Hazardous Waste Generation (10^6 MT)	1992** TRI Production-related Waste (10^6 MT)
Chemicals	28	300	1264	9.0
Petroleum	29	360	153	1.3
Primary Metals	33	112	1241	1.8
Electric\Electronic	36			0.4
Pulp & Paper	26	77	2043	1.1
Fabricated Metals	34			0.4

* Waste quantities include water fraction which can exceed 90%.

** Accounts for 84% of total TRI Production-related waste in 1992

The chemical sector stands out in accounting for about the half of the hazardous waste generated in the United States. The performance of detailed mass balance studies for this industrial sector is complicated by the variety of resources used as input materials, the use of intermediate chemicals in production, and the production of outputs that fall under several different SIC codes (e.g., chemicals 28 and petroleum 29) . As a result, environmental analyses of the chemical sector often rely on highly aggregated data and emphasize innovations in processing and other changes in practice that can improve environmental performance. Independent studies have amply shown the gains achievable through better plant maintenance and material substitution among other innovations. For a review of opportunities to improve environmental performance in the chemical industry see D. Allen, The Chemical Industry: Process Changes and the Search for Cleaner Technologies, pp. 233-273 in *Reducing Toxics*, R. Gottlieb, Ed., Island Press, 1995. For case studies on chemical plants that have reduce waste generation through a series of innovations in practice, materials selection, process modifications, etc. see INFORM, *Cutting Chemical Wastes*, INFORM, New York, 1985, and INFORM, *Environmental Dividends: Cutting More Chemical Wastes*, INFORM, New York, 1992.

In contrast to the chemical sector, the forest products sector relies on a highly uniform feed material (i.e., wood) and produces a relatively well defined class of output products. *Figure 3* shows a mass flow diagram for the forest product industry for 1993. The flow chart includes both the use of virgin feedstocks as well as streams of residues and recycled materials used in production. For a review of resource efficiency in the forest products sector see Ince, P.J., *Recycling of Wood and paper Products in the United States*, U.S. Dept. of Agriculture Forest

Service, 1994. Such analyses can reveal where leverage lies to reduce draw on the forest, municipal waste, or other environmental concerns. See for example, Wernick, I.K., Waggoner, P.E., and Ausubel, J.H., Searching for Leverage to Conserve Forests: The Industrial Ecology of Wood Products in the U.S., Journal of Industrial Ecology 1(3), in press, 1997.

Service sectors account for roughly three quarters of the annual Gross Domestic Product in the US. Though their environmental impact is not commensurate with this economic clout many of the activities associated with the service sector contribute significantly to environmental fallout. Studies of sectors such as health care, wholesale and retail trade, and communications focus on environmentally-important activities that support the provision of services and distribution of goods but are often hidden from the public eye. Studies in this area should assess issues like the transportation networks and energy needs associated with various service industries as well as direct material requirements for equipment ranging from the medical instruments to office paper and their disposal. Service industries can play a strategic environmental role in influencing their materials suppliers to act in an environmentally responsible manner as well as induce consumers to make environmentally responsible choices. Furthermore, a half hour along an interstate reading the signs on the trucks from Ben and Jerry's to Sears and air conditioning services shows how services dominate the distribution channels. For an example of environmentally oriented management in service industries see Bravo, C.E. 1995, A View of the United States Postal Service as a Service Sector Corporation, presented at the Fourth Annual NAE Workshop on Industrial Ecology, July 5-7, Woods, Hole, MA. Also see Guile, B.R. and Cohon, J.L., 1996, Services and the Environment: More questions than answers. Available from the National Academy of Engineering, Washington, D.C.

Unlike mining and manufacturing industries with visible, and sometimes massive, flows of materials no obvious strategy exists for examining sectors that provide medical services or deliver and sell goods. Research is needed to further develop a conceptual basis for addressing and evaluating the environmental impact of various service industries and to perform sector studies to test their hypotheses. For a rudimentary framework for assessing the environmental impact associated with the provision of services see Schmidt-Bleek, F., 1993, MIPS - A universal ecological measure?, *Fresenius Environmental Bulletin* 2:306-311.

Materials and energy flows correspond to some degree to money flows. Constructing materials accounts on the model of existing monetary input-output accounts of the economy encourages awareness, and clarifies understanding, of the use of physical resources in the economy, the addition of value to raw materials, and the amounts of waste generated in US industry. Input-output studies attempt to relate the effect of economic growth and technological innovation with the material input and output of economic sectors. One recent study examines the projected use and disposal of plastics in the US by linking a database describing plastics use per unit of sectoral output to an input-output database of the US economy. Expanding this framework to general material use will require researchers to estimate coefficients relating the consumption of specific materials to output across all economic sectors. Using a full set of coefficients, researchers could better estimate the cascade effects of activities, such as materials substitution and the diminished use of a given resource on other sectors and the resulting environmental impact. For an example of an input-output analysis of plastics in the US under different scenarios for consumer recycling see Duchin, F. and Lange, G., 1995, Prospects for the

Recycling of Plastics in the United States, *Structural Change and Economic Dynamics*, July 1995.

Geography-based mass balance studies can encompass localities, regions, and the nation as a whole. Though such studies blur local detail by relying on aggregated data, they can provide usefully comprehensive accounts of resource use and, depending on their scale, better locate the sources and sinks of major materials flows. At the national level, mass-balance studies allow resource managers to gauge the impact of federal policies on national resource use, determine per capita values for resource use, and plan strategically for the future. Research in this area should help clarify the difficulties in obtaining the necessary data for place-based mass-balance studies, including the need for better information on materials origin, identify data gaps, generate taxonomies for classifying resources, and specify the appropriate level of detail for materials accounts. As an example of a national materials account, Table 3 shows an account of materials inputs into the US economy in 1990. Such analyses should, again, help show where to seek leverage for environmental improvement.

LE 3

MATERIAL GROUP	APPARENT CONSUMPTION (MMT)		TOTAL US (MMT)	PER CAPITA PER DAY (kgs)
Energy	Coal	843		
	Crude Oil	667		
	Natural Gas	378		
	(Petroleum Products)	62	1950	21
Construction Minerals	Crushed Stone	1092		
	Sand & Gravel	828		
	Dimension Stone	1	1921	21
Industrial Minerals	Salt	41		
	Phosphate Rock	40		
	Clays	39		
	Industrial Sand & Gravel	25		
	Gypsum	23		
	Nitrogen Compounds	17		
	Lime	16		
	Sulfur	13		
	Cement (imported)	12		
	Other	24	223	4
Metals	Iron & Steel	100		
	Aluminum	5		
	Copper	2		
	Other	4	111	1
Forestry Products	Saw Timber	123		
	Pulpwood	73		
	Fuelwood	52		
	Other	13	260	3
Agriculture	Grains	220		
	Hay	133		
	Fruits & Vegetables	71		
	Milk & Milkfat	64		
	Sugar Crops	51		
	Oilseeds	45		
	Meat & Poultry	42		
	Other	5	631	7

Life Cycles of Products

From the mapping of material, we turn to analyzing a product throughout its life to learn its environmental impact. Used with rising frequency in this decade to study consumer products, Life Cycle Analysis (LCA) has been defined by the USEPA as a way to "evaluate the environmental effects associated with any given industrial activity from the initial gathering of raw materials from the earth until the point at which all residuals are returned to the earth." Several organizations have developed methods for LCA each using a different analytic approach to this complex activity. Regardless of the approach, several generic difficulties challenge LCA, including poor quality data, weak reasons or procedures for establishing analytic boundaries, and diverse values inherent in comparing environmental factors with no common objective, quantitative basis. The selection of products undergoing LCA to date has been haphazard, with several products receiving intense scrutiny while others are neglected almost completely. Consistent with the goal of establishing rigorous parameters for measuring the environmental impact of industrial activity, IE research properly focuses on each of these concerns about LCA

Comparing existing methods for LCA gives insight into the conceptual framework used by researchers. The Society for Environmental Toxicology and Chemistry (SETAC) 'Code of Practice' for LCA stands out currently as the most widely recognized procedural model. The Code divides LCA into four distinct components: 1) Scoping; 2) Compiling quantitative data on direct and indirect materials/energy inputs and waste emissions; 3) Impact assessment; and 4) Improvement assessment. While variations exist, the theme of taking an inventory and performing an assessment based on collected data is common to all LCA approaches dating back to the early 1970's.

Different methods for obtaining and presenting LCA results have evolved in response to the uncertainty associated with input data and the difficulty of reducing disparate indicators to a few meaningful numbers useful to managers and product designers. Methods for LCA differ in how they accommodate the need for qualitative analysis. LCAs variously denominate the value of environmental impact in kgs, dollars, square meters, and other numerical values. Continued research will shed light on what are the most effective methods for LCA and when can they be used in conjunction to reflect the multiple axes of environmental quality.

Though some methods for LCA receive approval for thoroughness and analytic consistency, these same methods have been criticized as requiring too much data, time, and money when each are in short supply. As an alternative method for assessing the environmental impact of products, researchers at AT&T have devised the Abridged Life Cycle Assessment Matrix, a method that couples quantitative environmental data with qualitative expert opinion into an analysis that conveys the uncertainty and multidimensionality of LCA and also yields a quantitative result. Table 4 shows an example of this LCA method in a comparison of the generic automobile of the 1950s and the 1990s. See Graedel, T.E., Allenby, B.R., and Comrie, P.R., 1995, Matrix Approaches to Abridged Life Cycle Assessment, *Environmental Science and Technology*, 29:134A-139A.

Table 4

Life cycle analysis: Comparing a 1950s and 1990s car

Generic 1950s automobile

Life Cycle Stage	Environmental Concern					
	Materials choice	Energy use	Solid residues	Liquid residues	Gaseous residues	Total
Premanufacture	2	2	3	3	2	12/20
Product manufacture	0	1	2	2	1	6/20
Product packaging and transport	3	2	3	4	2	14/20
Product use	1	0	1	1	0	3/20
Refurbishment-recycling-disposal	3	2	2	3	1	11/20
Total	9/20	7/20	11/20	13/20	6/20	46/100

Generic 1990s automobile

Life Cycle Stage	Environmental Concern					
	Materials choice	Energy use	Solid residues	Liquid residue s	Gaseous residues	Total
Premanufacture	3	3	3	3	3	15/20
Product manufacture	3	2	3	3	3	14/20
Product packaging and transport	3	3	3	4	3	16/20
Product use	1	2	2	3	2	10/20
Refurbishment-recycling-disposal	3	2	3	3	2	13/20
Total	13/20	12/20	14/20	16/20	13/20	68/100

Table 4. The two panels show environmental performance values for 1950s and 1990s generic American automobiles. This LCA method allows for broad comparison environmental performance at major stages of the product life cycle (e.g., product manufacture and product use) between two historical periods. Note, for exam the improved performance in product manufacture between the two periods, and also note the relatively low sc for product use still assessed in the 1990s. The best possible value for each cell is 4 and a maximum score is !
Source: Graedel, T.E., Allenby, B.R., and Comrie, P.R., 1995, Matrix Approaches to Abridged Life Cycle Assessment, *Environmental Science and Technology*, 29:134A-139A.

Research is needed to compare existing methods for LCA with an eye on their treatment of uncertain data, the weight given to various environmental parameters, and the format for presenting results. The aim of such research is the development of standardized methods for LCA that convey the data uncertainty and reflect the multidimensional character of environmental impacts caused by products. For a critical review of current methods for LCA see R.U. Ayres, 1995, Life Cycle Analysis: A Critique, *Resources Conservation and Recycling*, 14, 199-223. In the search for leverage, the question remains which products deserve an LCA and which do not.

Indicators

When we cannot measure a material within an industry or the components and fate of a product, our environmental knowledge is of a meager and unsatisfactory kind. The measurements must serve their purpose of navigation toward the goal of IE, revealing whether a great environmental impact is growing or shrinking in the long term, whether a policy is succeeding or failing, and differentiate the trivial from the deadly

In our vocabulary, measures or metrics show the tons needed to perform a materials-balance or life cycle analysis. Indicators combine measurements into an index of progress or regress broadly for an industry, firm, or policy. Like the Cost of Living Index or the Index of Leading Indicators, a suite of indicators tell a more reliable story than a single measure.

In line with the objectives of IE, metrics should measure the efficiency with which resources and energy are converted to useful products and byproducts in industry with metrics

such as product-to-waste ratios, and circulation and loss rates. These environmental metrics extend to all scales in the industrial system. At the global, national, and regional level the need is for metrics that integrate within and across industrial sectors, recognize the interdependence among them, and determine their combined effect on the population and environmental quality. For industrial sectors, research is needed to devise metrics that measure the average efficiency of materials use, identify the gap between leaders and followers in environmental performance, and examine the relative value of mandated as opposed to voluntary adoption of best environmental practices.

Metrics can isolate salient environmental variables that allow for more informed investigation of opportunities for synergism in the industrial system through the exchange of residual materials and energy. For firms, metrics should aim to provide measures of internal resource use and waste generation and the impact of products when they are consumed and disposed of. The challenge at this level is to devise meaningful environmental metrics that fit with existing benchmarks used to assess business operations, such as productivity, inventory accounting, and overhead costs. Several large US and European firms (e.g., 3M, AT&T, Novo Nordisk, Volvo) have incorporated environmental metrics into their business operations and have taken lead international positions in promoting improved environmental performance.

To show general progress in reducing environmental impacts the indicators must consistently link or relate the performance of a firm to that of an industry, or a region and nation. It must link an LCA to an analysis of material in a nation. The purpose of linkages is to avoid optimizing a single factory or sector at the expense of hurting the larger system's environmental performance. The same is true of geography-based metrics: community level assessments should

be coordinated with state-wide initiatives and contribute to achieving national goals for environmental quality. In developing a strategic environmental vision, the global optimization of the system should not be compromised by pursuing what are in fact only local maxima. Selecting the right scale for metrics is critical to ensuring that the system of interest is not arbitrarily defined and does not exclude relevant activities nor include too much that is irrelevant

Finally, metrics should be devised such that do assume or promote lock-in to current technologies that are inherently problematic while ignoring promising innovations that are fundamentally more environmentally sound. For instance, optimizing the environmental attributes of the personal automobile based on a gasoline powered internal combustion engine should not hinder the development of inherently cleaner, though not yet commercial, alternatives. The metrics should promote the understanding of industrial evolution and its possibilities

Discovering Dynamics in History

Research on the historical development of technological innovation and diffusion into society provides useful models for looking to the future and puts present performance in context. Historical rates yield the record of outcomes of technical and behavioral change, of political and economics forces all interacting. Patterns may also repeat from one nation to another. If historic rates for master processes such as decarbonization and dematerialization appear too slow to avert future problems, we might learn whether needed acceleration is within achieved experience or extraordinary. Most attempts to discover dynamics in history have been for the US and a few other industrialized countries for which good data are readily accessed. More effort needs to be applied to the records of China, India, and other countries, data permitting. For discussion of

rates of diffusion in space and time, see Gruebler, A., Time for a Change: On the Patterns of Diffusion of Innovation, *Daedalus 125(3)*: 19-42.

International Comparisons

As history can teach about the potential for change and its likely directions, so can international comparisons of practice in such fields as waste generation. Ongoing, comparative review of emerging strategies and frameworks for implementing IE in diverse countries would help shed light on efforts of each country. International comparisons yield insights into the roles, relative significance, and malleability of industrial structure, social organization, and culture as well as technology. For a decade-old comparison of environmental regimes in various countries which thus allows insight into both durable and transient national features, see Hoberg, G. Jr., 1986, Technology, Political Structure, and Social Regulation: A cross-national analysis, *Comparative Politics*, 18:357-376. For more information on IE activities in Japan see *Industrial Ecology: US/Japan Perspectives*, National Academy of Engineering, National Academy Press, 1994.

III. IMPLEMENTING INDUSTRIAL ECOLOGY

With means and measures for progress in IE, we turn to implementation. We group research on implementation into technical matters of the material basis and into institutional barriers and incentives.

a) The Technical Basis

Choosing the Material

IE research in the area of basic materials focuses on ways to increase the potential for reusing, recovering, and recycling materials used and generated by industry (including products, byproducts, and wastes) from the primary processing of materials and from actual industrial and consumer products leaving factories.

For instance, research on "smart materials" capable of sensing and responding to ambient changes in surrounding media as well as internal structural change offers the promise of reducing the mass necessary for different economic functions and saving the resources needed to replace failed structures through early detection and prevention. Research on surface and interfacial properties of materials could allow for more durable products that better resist corrosion and wear. Improving the strength-to-weight ratio and the thermal performance of materials can facilitate the development of transportation vehicles that require less mass to maintain structural integrity and allow engines to achieve greater thermodynamic efficiencies.

Anticipating the recycling that we shall discuss later, we note that choosing the right material can ease or retard recycling. Optimizing the performance features of materials often comes at the expense of increasing their complexity in products and heightening their sensitivity

to contaminants, for example, the low tolerance for contaminants in high performance metals with strict alloying ratios. This complexity complicates later efforts at reprocessing. In cases where complex materials are recovered, their presence in a mixture with other less or differently refined materials translates to downgrading the recovered materials to lower performance standards and thus forfeiting much of their initial value. Research on improving materials composition in products to better accommodate materials cycling as well as research on materials selection and process design must remain aware of the current technical and economic drivers in the materials industries (e.g., high throughput, materials efficiency, and increased value added) in pursuing technological innovation in this environmentally strategic industry.

Research on alternative methods for materials processing to reduce toxicity must consider both the selection of feed materials as well as the processes involved in all stages of production. In many cases more environmentally benign starting materials exist but can not be used with existing capital equipment. IE research on materials processes thus focuses on opportunities for modifying processes to accommodate different starter materials, minimizing toxics generation, and optimizing the character of products and byproducts for reuse.

Research on these topics is well established, but the salutary environmental dimension remains to be much more fully explored. Research on the end-of-life stage of materials and products needs to be increased. For a review of materials research needs for IE see *Basic Research Needs for Environmentally Responsive Technologies of the Future*, P. Eisenberger, Ed., Princeton Materials Institute, Princeton, NJ, 1996.

Designing the Product

Research to improve the environmental character of consumer products (i.e., Design for Environment) complements research on the component materials that comprise them. Here too the purpose of research is to help achieve the objective of a closed materials cycle. Research on product design should aim to minimize the waste generated during product manufacture, simplify the reuse of products and their components, and minimize energy consumption use and other negative impacts of product use. In general, product designers have greater flexibility in selecting the materials components of products, including the use of reprocessed materials, than is the case for primary materials processors. The evolution of the uses of cadmium illustrates how a hazardous material can be incorporated either in dangerously dissipative products such as paint or in much easier to contain and recycle products such as batteries (*Figure 4*).

The stage of product assembly also offers opportunity for reducing the use of toxic materials and minimizing wastes. Designing products to ease disassembly is of considerable practical importance to enable recovery. The less labor and capital equipment necessary for disassembly, the more economically attractive recovery becomes. Clever design can also reduce the amount of materials needed in a product, for instance, the use of lower gauge metal sheet in aluminum beverage cans. Research in each of these areas of product design can be complemented by Life Cycle Analysis to understand the tradeoffs that occur in optimizing one stage of the manufacturing process in isolation from others. For a review of strategies and design options for improving the environmental character of products see US Congress Office of Technology Assessment, *Green Products by Design: Choices for a Cleaner Environment*, OTA-E-541, Washington, DC, US Government Printing Office, 1992.

Manufactured "Products" in the marketplace include items made of distinct material components assembled into more complex forms as well as intricate blends of materials such as chemicals. They range in size from jumbo jets to children toys and from gasoline to shampoo. Selecting representative products for case studies provides concrete examples that illustrate the leverage of product design on the subsequent environmental attributes of products and the processes used to make them. The selection of products that reflect the wide variety of industrial and consumer products in the marketplace and the performance of detailed case studies looking at the possible design choices and their effects constitutes a further area of IE research. For a case study on the environmental design of the telephone see Sekutowski, J.C. 1994. Greening the Telephone: A Case Study. pp. 178-185 in *The Greening of Industrial Ecosystems*, B.R. Allenby and D.J. Richards, eds., National Academy Press, Washington, D.C. For a case study on the environmental design of household refrigerators see Naser, S.F., Keoleian, G.A., and Thompson, L.T., 1993, *Design of a CFC-Free, Energy Efficient Refrigerator*, Chemical Engineering Dept., University of Michigan, Ann Arbor. Available from the National Pollution Prevention Center, Ann Arbor, MI.

Recovering the Material

The minimizing of waste and so environmental impact by choosing the right materials and assembling them right continues with the reuse of materials. For mixtures of material the challenge for recovery lies in separation. Using humans to separate materials is both costly and inefficient. Furthermore, in some cases two materials (e.g., different plastic resins) may appear similar to the naked eye but may differ significantly in their chemical and physical properties.

Automated methods for materials separation are capable of detecting such differences by exploiting disparities in physical and chemical properties to distinguish between materials. Taking advantage of differences in particle size, density, and magnetic and optical properties o materials in municipal solid waste allows secondary materials processors to separate out organics, and ferrous and non-ferrous metals from waste streams. Sensor arrays and high speed computing capability now allow for real time identification and separation of different plastic resins in mixed waste streams.

For materials more intricately bound in waste streams, more sophisticated approaches are needed. Metals can be found in rinse waters from metal finishers, stack emissions and pollution control sludge from coal-fired power plants, and baghouse dusts from metal smelters among others. A range of technical approaches exist for recovering metals from wastes including electrolytic techniques (common in hydrometallurgical processes used for primary materials), acidic leaching (familiar to mining engineers) as well as a variety of membrane technologies. For a review of state of the art in the recovery of metals from complex solutions see Hager, J.P., et al., eds., 1994, *Extraction and Processing for the Treatment and Minimization of Wastes*, published by The Minerals, Metals, and Materials Society, Warrendale, PA.

Many tons of metals are annually lost to productive use as a result of their dilution or minute concentrations in wastes. In a national analysis of metals concentrations in waste streams in the US, researchers have found that metals concentrations are frequently higher in waste stream compared with those in typical ore bodies. This analysis was conducted using the "Sherwood Plot," which relates the selling price of a material with its degree of dilution in the matrix from which it is being separated. *Figure 5* shows the "Sherwood Plot" for resource

concentrations in their natural matrix and those found in US waste streams. Based on this analysis large amounts of valuable resources are annually discarded as a result of their being viewed as "wastes" (a phenomenon that reflects the regulatory, as opposed to technical, origin of this term). The analysis also demonstrates that in this instance enhanced materials recovery would not only provide environmental benefits but economic ones as well.

For each of the above areas, IE research can freshly synthesize knowledge on materials separation and recovery in an environmental framework. The research should include the identification of needs for improving existing recovery systems based on their demonstrated ability to isolate distinct materials as well as the need for new separation and recovery technologies. More advanced research in this area could explore opportunities for recovering materials that are currently dissipated (i.e., lost) through normal use, in cases where this is feasible. Lots of caustics and solvents go down our drains.

The massive quantities of several relatively safe, non-toxic wastes surely provide opportunities for recovery. These materials are often byproducts from large-scale industrial activity and, though mostly benign, may contain small amounts of trace contaminants. The largest of these waste streams are coal combustion byproducts (CCB) (i.e., fly and bottom ash, slag, and desulfurization sludge), averaging about 100 MMT annually in the US. Currently some fraction of this material is used in road aggregate and cement manufacture, however the majority of CCB continues to accumulate in waste piles. For an analysis of the uses CCB and other bulk wastes see Ahmed, I., *Use of Waste Materials in Highway Construction*, Noyes Data Corporation, Park Ridge, New Jersey, 1993. Also see Barsotti, A.F., and Kalyoncu, R.,

Implications of Flue Gas Desulfurization on the Mineral Industries, US Bureau of Mines (RIP), Washington, D.C., 1995.

Phosphogypsum provides an example of a bulk material where the presence of contaminants confounds efforts at recovery. Roughly 50 MMT of phosphogypsum are generated annually as a byproduct from the production of phosphoric acid, mostly used for producing fertilizer and animal feed, in the US. The use of phosphogypsum for road construction and as a cement additive is constrained by the presence of radionuclides (e.g., uranium-230 & 234, radium-226, and radon-222) and, in some cases, heavy metals (e.g., arsenic, chromium). Development continues on means for purifying this waste material for productive use. Other examples of large scale potentially reusable industrial waste flows include spent potliners from metals smelters and refractory materials used in glass manufacture.

Substituting these bulk materials in the economy directly displaces masses of virgin materials and thus avoids environmental disruption from mining and quarrying. The factors limiting fuller integration of these waste resources include the presence of contaminants and the costs associated with their transport. IE research on bulk industrial wastes should aim to neutralize the problems preventing greater recovery of these materials. Specifically, IE research should identify major sources and potential uses for bulk industrial wastes, clarify the type and level of contaminants found in them, point to the technologies involved in rendering wastes suitable for reuse, and analyze the further possibilities for their greater use in the economy.

Monitoring and Sensing Technology

Accurate empirical data on waste streams and other operational variables are a prerequisite for designing and using environmental performance measures in industry and for

implementing new processes and practices. Additionally, environmental monitoring of natural systems and the services they provide helps gauge pollution and its effects. The National Resources Inventory, concentrating on soil erosion and farming, illustrates the utility of such monitoring (Kellogg, RL, GW TeSelle, and JJ Goebel, 1994, Highlights from the 1992 National Resources Inventory, Journal of Soil and Water Conservation 49:521-527.) In areas such as agriculture and forestry research might consider how monitoring and sensing technologies can contribute to achieving greater efficiency, e.g., in application of chemicals. Research is also needed to develop reliable, low-cost monitoring systems for measuring total emissions to all environmental media stemming from an industrial facility. To consider a facility or ecopark inside a "bubble" we need to measure more than the smoke from one or a few chimneys or pipes

b) Institional barriers and incentives

Overcoming the technical barriers associated with recovering materials from waste streams is a necessary but insufficient step for stimulating the greater use of wastes in the economy. Technology making recovery cheap and assuring high quality input streams must be followed by encouraging regulations and easy informational access. Finally a ready market mus appear. Technologes are inseparable from institutional and social strategies. We need to learn why IE is not already the rule in industry and remove the impediments. Is this going to pay? From whose perspective? What balance of market-based, financial, regulatory, and legal strategies may dispose the industrial system to move in the desired direction at reasonable cost? For a conceptual introduction, see Frosch, R.A., 1996, Toward the End of Waste: Reflections on a New Ecology for Industry, *Daedalus* 125(3):199-212.

Market and Informational Barriers

Absent direct governmental interference, the markets for waste materials will ultimately rise or fall based on their economic vitality. Markets are sophisticated information processing machines whose strength resides in large part on the richness of the informational feedback available. The potential size and character of markets for what we currently label wastes remain open questions.

One option for waste markets are dedicated 'Waste Exchanges' where brokers trade industrial wastes like other commodities. By using internet technology to facilitate the flow of information, the need for centralized physical locations for either the stuff or for the traders in the stuff may be minimal. Research is needed on waste information systems that would form the basis for waste exchanges. Systems would need to list available industrial wastes as well as the means for buyers and sellers to access the information and conduct transactions. The degree to which such arrangements would allow direct trading or rely on the brokers to mediate transactions presents a further question. As part of the market analysis for waste materials, research is needed to understand past trends regarding the effect of price disparities between virgin and recovered materials, and to assess the effect of other economic factors associated with waste markets, such as additional processing and transportation costs. A further matter for investigation concerns whether some threshold level of industrial agglomeration is necessary to make such markets economically viable. For a recent review of this topic see USEPA, 1994. *Review of Industrial Waste Exchanges*, Report # EPA-530-K-94-003, Waste Minimization Branch, Office of Solid Waste, USEPA, Washington, D.C.

Progress is already being made on this front. The Chicago Board of Trade (CBOT), working with several government agencies and trade associations, has begun a financial exchange for trading scrap materials. Other exchanges such as the National Materials Exchange Network (NMEN) and the Global Recycling Network (GRN) facilitate the exchange of both materials recovered from municipal waste streams and of industrial wastes. Analysts might propose ideas for improving or facilitating the development of these exchanges. The value of such exchanges as a means of improving the flow of information depends on the deficiency of the current information flow, and how much this particular aspect of recycling plays in recycling's success or failure. The CBOT is different from the other exchanges in that it is a financial market -- starting now as a cash exchange with hopes that it will evolve into a forward and/or futures market.

A simple waste exchange is premised on the notion that opportunities for exchange are going unrealized. A cash exchange has a related premise that there is a need for what economists call price discovery. Finally, a futures or forward market exists to allow the risk associated with price volatility to be traded independent of the commodity.

The value of mechanisms such as the CBOT may be indirect, that is, price discovery may not be the main problem in the recyclables market, though important in some circumstances. Similarly, creating a market for buying and selling price risk through futures or forward contracts is useful but not likely to be extensive in the near term. The real value in the CBOT-type scheme may prove to be infrastructure and standards that it brings. The existence of the CBOT recyclables exchange requires specifications for scrap materials sufficiently robust that distant

entities can trade sight unseen. Further, the CBOT system has forced the creation of dispute arbitration mechanisms. Analysts need to watch such developments and report on them.

Business and Financial

The private firm is the basic economic unit and collectively constitutes the mechanism for reducing inventions and innovations to practice, in service of environmental quality or other goals. Corporations employ a spectrum of organizational approaches to handle environmental matters. In some cases the environment division of a corporation concerns itself exclusively with regulatory compliance and the avoidance of civil liability for environmental matters. For other firms the environment plays a more strategic role in corporate decision making. Decisions made at the executive level strongly determine whether or not companies adopt new technologies and practices that will effect their environmental performance. Relatedly, the manner in which corporations integrate environmental costs into their accounting systems, for instance how to assign disposal costs, bears heavily on its ability to make both short and long term environmentally responsible decisions.

Research is needed to understand better the role of corporate organization and accounting practices in improving environmental performance and the incentives to which corporations respond for adopting new practices and technologies. Such studies would examine the learning process in corporate environments as well as investigate how corporate culture influences the ultimate adoption or rejection of environmentally innovative practices. For a study on the influence of corporate organization and culture on environmental decision making see Porter, M.E. and van der Linde, C., 1995, Toward a New Conception of the Environment-Competitiveness

Relationship, *Journal of Economic Perspectives* 9(4).xx-xx. For an analysis of the current methods for integrating environmental costs into corporate accounting systems see Ditz, D , Ranganathan, J., and Banks, R.D., *Green Ledgers: Case Studies in Corporate Environmental Accounting*, World Resources Institute, 1995.

Several management/learning approaches (e.g., Total Quality Management, High Performance Workplace, Lean Production) currently enjoy widespread recognition in business. Many of the efficiency enhancing practices advocated by these approaches bear strong resemblance to those of IE, for example, the stress on performance measures and improved information flows. Research is needed to integrate IE principles into the framework of TQM and other management/learning approaches now widely recognized in diverse industries For discussion of the new environmental context for private firms, see Allenby, B R , Evolution of the Private Firm in an Environmentally Constrained World, *The Industrial Green Game Implications for environmental design and management*, D J. Richards, ed , National Academy Press, Washington, D.C., in press

Regulatory

Environmental regulation strongly induces companies to appreciate the environmental dimensions of their operations. Businesses must respond to local, national, and international regulatory structures established to protect environmental quality. Although few question that regulations have helped to improve environmental quality, many argue that wiser, less commanding regulation would improve quality further at less cost. Agreements on hazardous waste tightly regulate the transport of these wastes across state and national boundaries, perhaps

reducing opportunities for re-use and encouraging greater extraction of virgin stocks. Elements of the US federal regulatory apparatus for wastes, (e.g., RCRA and CERCLA) heavily regulate the storage and transport of wastes and dictate waste treatment methods that also serve to dissuade later efforts at materials recovery. Research is needed to determine the role of past and current environmental regulation in encouraging or discouraging materials recovery efforts.

With better understanding of the effects of past regulation, researchers could explore regulatory reforms to provide greater incentive to recover materials from waste. This line of inquiry into the effect of regulatory reform should include a broader analysis of policies that favor more environmentally sound industrial ecosystems, such as rewarding firms that exploit materials symbioses within and between facilities, providing incentives for investment in capital equipment that uses secondary materials inputs, promoting manufacturer responsibility for product after their useful life (i e , takeback legislation), encouraging disposal practices that do not prevent later access to materials, and discontinuing subsidies to virgin materials producers. For a discussion of the design and implications of takeback legislation see Lifset, R , 1993, Take it Back: Extended producer responsibility as a form of incentive-based environmental policy, *Journal of Resource Management and Technology* 21(4):163-175.

Legal

Like regulation, the risk of civil liability from handling industrial waste also affects how much is recycled. The question of how developments in liability law affect decisions on the recovery of wastes from materials thus forms a further area for IE research. Such research would also investigate the potential for legal reforms that would facilitate greater materials recovery, for

instance by limiting the responsibility of parties handling wastes, while maintaining the societal protection that the statutes were meant to ensure.

Though ostensibly unrelated to environmental law, a host of other statutory bodies can affect the development of efficient industrial ecosystems. Anti-trust statutes can effectively bar the agglomeration of enterprises necessary to effectively close materials loops. Consumer protection law can encumber efforts to improve the environmental design of products. Law governing external trade impact international resource allocation as well as the transport of recoverable wastes. Legal decisions relating to government procurement practices can also help or hurt markets for recovered materials and can directly exert pressure environmentally important sectors. The prime motivations for these laws (or rules) are usually not environmental. However, research in this area can identify cases where environmental considerations may indicate reforms that do not interfere with the otherwise desired political, social, or economic effect. For an extended discussion on the environmental dimension of trade law see Esty, D.C., 1994, Greening the GATT: Trade, environment, and the future, Institute for International Economics, Washington, D.C.

Comparisons among policies and firms was one of the promised benefits of indicators and metrics. Studies in business, regulation, and law can yield similar benefits. The studies should advance IE's goal of lightening the environmental impact per person and per dollar.

Regional Strategies

Often geographic regions may provide a sensible basis for implementing IE. Industries tend to form spatial clusters in specific geographic regions based on factors such as access to raw

materials, convenient transportation, technical expertise, and markets. This is particularly true for 'heavy' industries requiring large resource inputs and generating extensive waste quantities. Furthermore, the industries supporting large industrial complexes tend to be located within reasonable proximity to their principal customers. These compact complexes, such as the steel industry around the southern Great Lakes, provide excellent subjects for the flow charts of industrial ecology. Research can investigate the geographic, economic, political and other factors that contribute to the development of symbiotic materials flows among industries in a region and overall regional environmental performance. Due to the unique character of different regions this work could proceed in the form of case studies of regions containing a concentration of industries in a particular sector, for example, the steel industry in the southern Great Lake states.

Still more compact and so more ideal subject for IE are Ecoparks. They are industrial facilities clustered to minimize both energy and material wastes through the internal bartering and external sales of wastes. One industrial park located in Kalundborg, Denmark has established a prototype for efficient reuse of bulk materials and energy wastes among industrial facilities (*Figure 6*). The park houses a petroleum refinery, power plant, pharmaceutical plant, wallboard manufacturer, and fish farm that have established dedicated streams of processing wastes (including heat) between facilities in the park. Figure 6 shows a schematic diagram of the Kalundborg Industrial Ecopark. Research should investigate the prospects for similar industrial ecoparks. Factors include the need for high quality inputs streams a nd the reliability of supplies What are the, business reasons for failure? Will Ecoparks self assemble? Research could also more broadly address the question of what spatial scales are most advantageous and practical for

the establishment of regional industrial networks. Must they be physically co-located or is there a limited range of proximities for which regional networks could operate effectively?

IV. CONCLUSION

Industrial ecology is both a job and a discipline. As a discipline, industrial ecology seeks to provide rigorous technical understanding that fosters systems of production and consumption that can be sustained for very long periods of time, even indefinitely, without significant environmental harm. IE takes a systems view of industry in developing strategies to facilitate more efficient use of material and energy resources and to reduce the release of hazardous as well as non-hazardous wastes to the environment. The ultimate objective of the field is the emergence of an economy that cycles virtually all of the materials it uses, emitting only micro amounts of wastes and pollutants, while providing high and increasing services to the large human population already here and still likely to grow. For the United States, at least a factor of ten improvement in emissions per dollar of GDP seems needed during the next century.

Research on goals and concepts sets the framework of IE. An underlying question is what is to be learned from the analogy between natural and industrial ecosystems. Exploiting the biological analogy, how can we better understand the evolution of industrial metabolism and resource consumption in industrialized society and can we extract patterns of development that explain the past use of resources and indicate likely futures? Indispensable to this activity are accurate accounts of the size and structure of current resource use, and deeper understanding of the environmental implications of the manufacture, distribution, use, and disposal of present products.

Tracking the flow of an individual chemical element from initial extraction to final disposition usefully highlights the industries using that element and indicates opportunities for conserving resources and limiting harmful exposures. Following the resource needs and wast

generation in individual firms and whole industrial sectors provides public and private managers the means to assess the environmental performance of a given firm or sector, learn more about the network of materials flows wherever they may lead, and isolate the factors and forces driving network development.

Research on implementation lies at the heart of IE as an applied science. Implementing IE in the diverse industries that form the economy will require both technological innovations and economic, regulatory, and legal incentives, or at least fewer disincentives. Technical research should focus on materials, products, and processes that lead to reduced resource use and waste generation in industry. Complementary efforts should consider the organizational factors and incentives that affect the ability of corporations and other actors to make operational changes that lead to improved environmental performance. Regional studies underscore the possibilities for cycling materials through local industrial networks and shed light on the impact of local or regional industrial activity on surrounding populations and landscapes.

First one and then another road may be the best route to the goal of IE. Research underlies them all. Improved means to work together, such as a research network on metals, are needed and must be actively considered during the next phase of the development of the field. At this stage, wisdom suggests that the research community limit the agenda of IE and do the limited work well. We should seek to answer specific questions that will produce environmental returns. For example, how shall we combine the harm per kilogram with the kilograms of wastes to guide control measures to the most important wastes and chart our progress in minimizing environmental impact? What indices will integrate environmental impact and so reveal success

or failure in terms of the costs of such things as choice of material or product design or recovery of material?

Industrial ecology began with a shared intuition that a vastly superior economy for the environment is both technically feasible and necessary if the economy is to grow. The rough drawings we have been able to make so far are encouraging, and history seems to be on our side. Properly elaborated during the coming years, industrial ecology could show where the most powerful levers are, efficiently guiding us to the means for a lean, durable, and highly productive economy.

V. BIBLIOGRAPHY

The following bibliography lists publications that deal explicitly with industrial ecology as an area of research as well as related literature. The structure of the bibliography corresponds to the categories used in this report and also adds sections for cross-cutting references and relevant scholarly journals. The subsequent list of web sites can only hint at the rapidly evolving state of electronic information resources.

For publications explicitly or clearly within industrial ecology we have endeavored to sample the work of recognized active authors and researchers in this area. As regards the more general, related environmental literature cited, we have selected references to illustrate substantive analyses that may inform and contribute to industrial ecology research. References appear in chronological order within each section.

For excellent, complementary bibliographies, see Erkman, S., 1997, Industrial Ecology: A Historical View, *Journal of Cleaner Production*, in press; and Erkman, S , 1994, Ecologie industrielle, metabolisme industriel, et societe d'utilisation, Etude effectuee pour la Fondation pour le progres de l'homme, Geneva, e-mail: serkman@vtx.ch

Introduction (The Goal and the Role)

Ausubel, J.H., 1996, Can Technology Spare the Earth?, *American Scientist*, 84(3):166-178.

O'Rourke, D., Connelly, L , and Koshland, C.P., Industrial Ecology: A Critical Review, 1996, *International Journal of Environment and Pollution* 6(2/3):89-112.

Schulze, P., ed., 1996, *Engineering Within Ecological Constraints*, National Academy Press, Washington, D.C.

Cohen, J.E., 1995, *How Many People Can the Earth Support?*, Norton, New York.

Frosch, R.A., 1995, Industrial Ecology: Adapting Technology for a Sustainable World, *Environment* 37(10):16-37.

Graedel, T.E., and Allenby, B.R., 1995, *Industrial Ecology*, Prentice Hall, Englewood Cliffs, NJ.

Lowe, E. and Evans, L., 1995, Industrial Ecology and Industrial Ecosystems, *Journal of Cleaner Production*, 3(1-2).

Allenby, B.R., 1994, Industrial Ecology Gets Down to Earth, *Circuits and Devices*, January '94 pp. 24-28.

Allenby, B.R. and Richards, D.J., eds., 1994, *The Greening of Industrial Ecosystems*, National Academy Press, Washington, D.C.

Frosch , R.A., 1994, Industrial Ecology: Minimizing the Impact of Industrial Waste, *Physics Today*, 47(11):63-8.

Socolow, R , 1994, Six Perspectives from Industrial Ecology, p. 3-16 in *Industrial Ecology and Global Change*, Socolow, R., Andrews, C., Berkhout, F., and Thomas V , eds., Cambridge University Press, New York.

Allenby, B R., 1992, Achieving Sustainable Development Through Industrial Ecology, *International Environmental Affairs*, 4(1) 56-68.

Ayres, R.U. and Simonis, U., eds., 1992, *Industrial Metabolism*, United Nations University Press, Tokyo, Japan.

Ausubel, J H , 1992, Industrial Ecology: Reflections on a Colloquium, *Proceedings of the National Academy of Sciences of the USA* 89(3):879-884.

Ehrenfeld, J R. 1992, Industrial Ecology A Technological Approach to Sustainability, *Hazardous Waste & Hazardous Materials* 9(3):209-211.

Frosch, R.A , 1992, Industrial Ecology: A Philosophical Introduction, *Proceedings of the National Academy of Sciences of the USA* 89(3):800-803.

Jelinski, L W., Graedel, T.E., Laudise, R.D , McCall, W , and Patel, C.K.N , 1992, Industrial Ecology: Concepts and Approaches, *Proceedings of the National Academy of Sciences of the USA* 89(3) 793-797.

Tibbs, H , 1992, Industrial Ecology: An Environmental Agenda for Industry, *Whole Earth Review*, Winter 1992. Pp. 4-19.

Ausubel, J H and Sladovich, H.E., eds , 1989, *Technology and Environment*, National Acade Washington DC.

Frosch, R A and Gallopoulos, N.E , 1989. Strategies for Manufacturing, *Scientific American*, September 1989, pp. 144-152.

Huisingh, D , 1989, Waste Reduction at the Source· The Economic and Ecological Imperative for Now and the 21st Century, pp. 96-111 in *Management of Hazardous Materials and Wastes: Treatment, Minimization, and Environmental Impacts*, Majumdar, S.K., et al., eds., Pennsylvania Academy of Sciences.

Marchetti, C., 1979, On 10^{12}: A Check on the Earth-Carrying Capacity for Man, *Energy 4*:1107-1117.

Ayres, R.U., 1978, *Resources, Environment and Economics: Applications of the Materials/Energy Balance Principle,* John Wiley & Sons, New York.

How Industrial Ecology Got its Name

Graedel, T.E., 1996, On the Concept of Industrial Ecology, *Annual Review of Energy and Environment,* Volume 21.

Allaby, M. ed., 1994, *The Concise Oxford Dictionary of Ecology,* Oxford University Press, Oxford, U.K.

Allenby, B.R. and Cooper, W.E., 1994, Understanding Industrial Ecology from a Biological Systems Perspective, *Total Quality Environmental Management*, Spring 1994 pp. 343-354.

Odum, E. 1989, *Ecology and Our Endangered Life-Support Systems*, Sinnauer Associates, Sunderland, MA.

Odum, H.T., 1988, Self-Organization, Transformity, and Information, *Science* 242:1132-1139.

Holling, C.S., 1986, Resilience of Ecosystems, Local Surprises and Global Change, pp. 292-317 in Clark, W.C. and Munns, R.E., eds., *Sustainable Development of the Biosphere*, Cambridge University Press, Cambridge, U.K.

Odum, H.T., 1986, *Ecosystem Theory and Application,* John Wiley and Sons, New York.

Holling, C.S., ed., 1978, *Adaptive Environmental Assessment and Management*, John Wiley and Sons, London, U.K.

Zero Emission Systems

Iantovksi, E., and Mathieu, P., Highly Efficient Zero Emission CO_2-Based Power Plant, University of Liege, Dept. of Nuclear Engineering and Power Plants, Belgium.

Lave, L.B., Hendrickson, C.T., and McMichael, F.C., 1995, Environmental Implications of Electric Cars, *Science* 268:993-5.

Allam, R.J., and Spilsbury, C.G., 1992, A Study of the Extraction of CO_2 from the Flue Gas of a 500 MW Pulverised Coal Fired Boiler, *Energy Conversion and Management 33(5-8)*:373-378.

Allenby, B.R. and Richards, D.J., eds., 1994, *The Greening of Industrial Ecosystems*, National Academy Press, Washington, D.C.

Frosch , R.A., 1994, Industrial Ecology: Minimizing the Impact of Industrial Waste, *Physics Today*, 47(11):63-8.

Socolow, R , 1994, Six Perspectives from Industrial Ecology, p. 3-16 in *Industrial Ecology and Global Change*, Socolow, R., Andrews, C., Berkhout, F., and Thomas V., eds., Cambridge University Press, New York.

Allenby, B.R , 1992, Achieving Sustainable Development Through Industrial Ecology, *International Environmental Affairs*, 4(1):56-68.

Ayres, R.U. and Simonis, U., eds., 1992, *Industrial Metabolism*, United Nations University Press, Tokyo, Japan.

Ausubel, J H , 1992, Industrial Ecology: Reflections on a Colloquium, *Proceedings of the National Academy of Sciences of the USA* 89(3):879-884.

Ehrenfeld, J R. 1992, Industrial Ecology: A Technological Approach to Sustainability, *Hazardous Waste & Hazardous Materials* 9(3):209-211.

Frosch, R.A , 1992, Industrial Ecology: A Philosophical Introduction, *Proceedings of the National Academy of Sciences of the USA* 89(3):800-803.

Jelinski, L W , Graedel, T.E., Laudise, R D , McCall, W , and Patel, C.K N , 1992, Industrial Ecology: Concepts and Approaches, *Proceedings of the National Academy of Sciences of the USA* 89(3) 793-797.

Tibbs, H., 1992, Industrial Ecology: An Environmental Agenda for Industry, *Whole Earth Review*, Winter 1992. Pp. 4-19.

Ausubel, J.H and Sladovich, H.E., eds , 1989, *Technology and Environment*, National Acade Washington DC.

Frosch, R.A. and Gallopoulos, N.E , 1989, Strategies for Manufacturing, *Scientific American* September 1989, pp. 144-152.

Huisingh, D . 1989, Waste Reduction at the Source. The Economic and Ecological Imperativ for Now and the 21st Century, pp. 96-111 in *Management of Hazardous Materials and Wast Treatment, Minimization, and Environmental Impacts*, Majumdar, S K., et al., eds., Pennsylv Academy of Sciences.

Marchetti, C., 1979, On 10^{12}: A Check on the Earth-Carrying Capacity for Man, *Energy 4*:1107-1117.

Ayres, R.U., 1978, *Resources, Environment and Economics: Applications of the Materials/Energy Balance Principle,* John Wiley & Sons, New York.

How Industrial Ecology Got its Name

Graedel, T.E., 1996, On the Concept of Industrial Ecology, *Annual Review of Energy and Environment,* Volume 21.

Allaby, M. ed., 1994, *The Concise Oxford Dictionary of Ecology,* Oxford University Press, Oxford, U.K.

Allenby, B.R. and Cooper, W.E., 1994, Understanding Industrial Ecology from a Biological Systems Perspective, *Total Quality Environmental Management*, Spring 1994 pp. 343-354.

Odum, E. 1989, *Ecology and Our Endangered Life-Support Systems*, Sinnauer Associates, Sunderland, MA.

Odum, H.T., 1988, Self-Organization, Transformity, and Information, *Science* 242:1132-1139.

Holling, C.S., 1986, Resilience of Ecosystems, Local Surprises and Global Change, pp. 292-317 in Clark, W.C. and Munns, R.E., eds., *Sustainable Development of the Biosphere*, Cambridge University Press, Cambridge, U.K.

Odum, H.T., 1986, *Ecosystem Theory and Application,* John Wiley and Sons, New York.

Holling, C.S., ed., 1978, *Adaptive Environmental Assessment and Management*, John Wiley and Sons, London, U.K.

Zero Emission Systems

Iantovksi, E., and Mathieu, P., Highly Efficient Zero Emission CO_2-Based Power Plant, University of Liege, Dept. of Nuclear Engineering and Power Plants, Belgium.

Lave, L.B., Hendrickson, C.T., and McMichael, F.C., 1995, Environmental Implications of Electric Cars, *Science* 268:993-5.

Allam, R.J., and Spilsbury, C.G., 1992, A Study of the Extraction of CO_2 from the Flue Gas of a 500 MW Pulverised Coal Fired Boiler, *Energy Conversion and Management 33(5-8)*:373-378.

Marchetti, C., 1989, How to Solve the CO_2 Problem Without Tears, *International Journal of Hydrogen Energy* 14(8):493-506

Lee, T.H., 1989, Advanced Fossil Fuel Systems and Beyond, pp. 114-136 in Ausubel, J.H., and Sladovich, H.E., eds., *Technology and Environment*, National Academy, Washington DC.

Hafele, W., Barnert H., Messner, S., Strubegger, M., and Anderer, J., 1986, Novel Integrated Energy Systems: The Case of Zero Emissions, pp. 171-193 in Clark, W.C. and Munns, R.E., eds., *Sustainable Development of the Biosphere*, Cambridge University, Cambridge, U.K.

Materials Substitution and Dematerialization

Wernick, I.K., Herman, R., Govind, S., and Ausubel, J.H., 1996, Materialization and Dematerialization: Measures and Trends, *Daedalus* 125(3):171-198

Wernick, I.K., 1994, Dematerialization and Secondary Materials Recovery: A Long-Run Perspective, *Journal of the Minerals, Metals, and Materials Society*, 46(4):39-42.

Bernardini, O. and Galli, R., 1993, Dematerialization: Long Term Trends in the Intensity of Use of Materials and Energy, *Futures* 25(4):431-448.

Rogich, D.G. and Staff, 1993, *Materials Use, Economic Growth, and the Environment*, Presented at the International Recycling Congress and REC'93 Trade Fair, U.S. Bureau of Mines, Washington, D.C.

Sousa, L.J., 1992, *Towards a New Materials Paradigm*, U.S. Bureau of Mines, Washington, D.C.

U.S. Bureau of Mines, 1990, *The New Materials Society: Volume I-III*, U.S. Government Printing Office, Washington, D.C.

Herman, R., Ardekani, S.A., and Ausubel, J.H., 1989, Dematerialization, pp. 50-69 in *Technology and Environment*, Ausubel, J.H. and Sladovich, H.E., eds., National Academy Press, Washington, D.C.

Waddell, L.M. and Labys, W.C., 1988, Transmaterialization: Technology and Materials Demand Cycles, *Materials and Society* 12(1):59-86.

Williams, R.H., Larson, E.D., and Ross, M.H., 1987, Materials, Affluence and Industrial Energy Use, *Annual Review of Energy and Environment* (12):99-144.

Tilton, J.E., ed., 1983, *Materials Substitution: Lessons from the Tin-Using Industries*, Resources for the Future, Inc., Washington, D.C.

Spencer, V.E., 1980, *Raw Materials in the United States Economy 1900-1977*, Bureau of the Census Technical paper No. 47, U.S. Department of Commerce/U.S. Department of the Interior, Washington D.C.

Malenbaum, W., 1978, *World Demand for Raw Materials in 1985 and 2000*, McGraw-Hill, New York.

Goeller, H.E. and Weinberg, A.M., 1976, The Age of Substitutability: What do we do when the mercury runs out, *Science* 191:683-689.

Functionality Economy

Stahel W R., 1994, The Utilization-Focused Service Economy: Efficiency and Product-Life Extension, pp. 178-190 in *The Greening of Industrial Ecosystems*, B.R. Allenby and D.J Richards, eds.

Stahel, W.R , 1993, *Product Design and Utilization*, The Product Life Institute, Geneva, Switzerland.

Materials Flow and Balance Analysis

Wernick, I K , Waggoner, P.E , and Ausubel, J H , Searching for Leverage to Conserve Forests: The Industrial Ecology of Wood Products in the U.S , *Journal of Industrial Ecology 1(3)*, in press, 1997

Ayres, R U. and Ayres, L W , The Life-Cycle of Chlorine: Part I-IV, *Journal of Industrial Ecology*, 1(1), in press, 1997.

Ayres, R.U. and Ayres, L.W , Use of Material Balances to Estimate Aggregate Waste Generation in the United States (Excluding Chemicals), in *Measures of Environmental Performance and Ecosystem Condition*, P. Schulze ed., National Academy Press, Washington, D.C., in press, 1997.

Kleijn, R , Tukker, A., and van der Voer, E , Chlorine in the Netherlands: Part I, *Journal of Industrial Ecology*, in press, 1997.

Sagar, A.D and Frosch R. A., Industrial Ecology: A Perspective and an Example, *Journal of Clean Technology*, in press, 1997.

Ayres, R U. and Ayres, L.W., 1996, *Industrial Ecology: Towards Closing the Materials Cycle*, Edward Elgar Publishing, Cheltenham, U.K.

Duchin, F. and Lange, G., 1995, Prospects for the Recycling of Plastics in the United States, *Structural Change and Economic Dynamics*, July 1995.

Environmental Defense Fund et al., 1995, *Paper Task Force Recommendations for Purchasing and Using Environmentally Preferable Paper,* Final Report & Technical Supplements I-V, (Duke University, Environmental Defense Fund, Johnson & Johnson, McDonald's, The Prudential Insurance Company of America, Time Inc.), Published by the Environmental Defense Fund, New York.

Wernick, I.K. and Ausubel, J.H., 1995, National Materials Flows and the Environment, *Annual Review of Energy and Environment*, 20:462-492.

Thomas, V.M. and Spiro, T.J , 1995, An Estimation of Dioxin Emissions in the United States, *Toxicological and Environmental Chemistry,* (50):1-37.

Ayres, R.U. and Ayres, L.W , 1994, *Chemical Industry Wastes: A Materials Balance Analysis,* INSEAD, Fontainebleau, France.

Ince, P.J., 1994, *Recycling of Wood and Paper Products in the United States*, U S. Dept. of Agriculture Forest Service, paper delivered at United Nations Economic Commission for Europe Timber Committee Team of Specialists on New Products, Recycling, Markets, and Applications for Forest Products, June 1994. Copies available from USDA Forest Service Forest Products Laboratory, Madison Wisconsin, 53705, USA.

Kinzig, A.P. and Socolow, R H , 1994, Human Impacts on the Nitrogen Cycle, *Physics Today* 47:24-31.

Lave, L., Cobas-Flores, E , Hendrickson, C.T., McMichael, F.C., 1995, Using Input-Output Analysis to Estimate Economy-Wide Discharges, *Environmental Science and Technology* 29(9):420A-426A.

Duchin, F., 1992, Industrial Input-Output Analysis: Implications for Industrial Ecology, *Proceedings of the National Academy of Sciences of the USA* 89(3):851-855.

Stigliani, W.M. and Anderberg, S , 1992, *Industrial Metabolism at the Regional Level: The Rhine Basin,* International Institute for Applied Systems Analysis, Laxenburg, Austria.

Thornton, I., 1992, Sources and Pathways of Cadmium in the Environment, *IARC Scientific Publications* 118:149-62, Lyon, France.

Life Cycles of Products

Ayres, R.U , 1995, Life Cycle Analysis: A Critique, *Resources Conservation and Recycling.* 14:199-223.

Graedel, T.E., Allenby, B.R., and Comrie, P R., 1995, Matrix Approaches to Abridged Life Cycle Assessment, *Environmental Science and Technology*, 29:134A-139A.

Narodoslawsky, M., Krotscheck, C., 1995, The Sustainable Process Index (SPI): Evaluating Process According to Environmental Compatibility, *Journal of Hazardous Materials*, 14(2-3):383-397.

Weitz, K.A., Malkin, M., and Baskir, J.N., eds., 1995, *Streamlining Life-Cycle Assessment Conference and Workshop*, Research Triangle Institute, Research Triangle Park, NC.

Organization for Economic Co-operation and Development, *Life-Cycle Management and Trade*, 1994, Paris, France.

Klimisch, R.L., 1994, Designing the Modern Automobile for Recycling, pp. 172-178 in *The Greening of Industrial Ecosystems*, B.R. Allenby and D.J. Richards, eds., National Academy Press, Washington, D.C.

Sekutowski, J.C., 1994, Greening the Telephone: A Case Study, pp. 178-185 in *The Greening of Industrial Ecosystems*, B.R. Allenby and D.J. Richards, eds., National Academy Press, Washington, D.C.

Society of Environmental Toxicology and Chemistry [SETAC], 1994, *Life-Cycle Assessment Data Quality: A Conceptual Framework*, SETAC, Pensacola, FL.

Curran, M.A., 1993, Broad-Based Environmental Life Cycle Assessment, *Environmental Science and Technology* 27(3):431-436.

Naser, S.F., Keoleian, G.A., and Thompson, L.T., 1993, *Design of a CFC-Free, Energy Efficient Refrigerator*, Chemical Engineering Dept., University of Michigan, Available from the National Pollution Prevention Center, Ann Arbor, MI.

Sage, J., 1993, Industrielle Abfallvermeidung und deren Bewertung am Beispiel der Leiterplattenherstellung, dbv-Verlag, Technische Universitat Graz, Austria. [Describes Sustainable Process Index method for LCA]

Schmidt-Bleek, F., 1993, MIPS - A Universal Ecological Measure?, *Fresenius Environmental Bulletin* 2:306-311.

Society of Environmental Toxicology and Chemistry, 1993, *Guidelines for Life-Cycle Assessment: A "Code of Practice,"* SETAC, Pensacola, FL.

U.S. Environmental Protection Agency, 1993, *Life-Cycle Assessment: Inventory Guidelines and Principles*, EPA Report no. EPA/600/R-92/245, USEPA, Office of Research and Development, Washington, D.C.

Fava, J.A., ed., 1991, *A Technical Framework for Life-Cycle Assessments,* Society of Environmental Toxicology and Chemistry, Washington D.C.

Hocking, M.B., 1991, Paper Versus Polystyrene: A Complex Choice, *Science* 251:504-505.

Lubkert, B., Virtanen, Y., Muhlberger, M., Ingman, I., Vallance, B., and Alber, S., 1991, *Life Cycle Analysis: IDEA an International Database for Ecoprofile Analysis*, International System for Applied Systems Analysis, Laxenburg, Austria.

Steen, B. and Ryding, S-O., 1991, The EPS Environmental Accounting Method: An Application of Environmental Accounting Principles for Evaluation and Valuation of Environmental Impact in Product Design, Swedish Environmental Research Institute, Goetberg, Sweden.

Ahbe, S., Braunschweig, A., and Mueller-Wenk, R., 1990, Methodik fuer Oekobilanzen auf der Basis Oekologischer Optimierung, Schriftenreihe Unwelt Nr. 133, Bundestat fuer Unwelt, Wald and Landschaft (BUWAL), Bern, Switzerland. [Describes Swiss Eco-Points method for LCA]

Indicators

Adriaanse, A., Bringezu, S., Hammond, A., Moriguchi, Y., Rodenburg, E., Rogich, D., and Schuetz, H., 1997, *Resource Flows: The Material Basis of Industrial Economies*, joint publication of World Resources Institute, Wuppertal Institute for Climate, Environment and Energy, Netherlands Ministry of Housing, Planning, and Environment, and National Institute for Environmental Studies, available from World Resources Institute, Washington DC.

Wernick, I.K., and Ausubel, J H., 1995, National Materials Metrics for Industrial Ecology, *Resources Policy 21(3)*:189-198.

Discovering Dynamics in History

Ausubel, J.H., ed., 1997, *Technological Trajectories and the Human Environment*, National Academy Press, Washington, D.C.

Gruebler, A., 1996, Time for a Change: On the Patterns of Diffusion of Innovation, *Daedalus 125(3)*: 19-42.

Curzio, A.Q , Fortis, M., and Zoboli, R , eds., 1994, *Innovation, Resources, and Economic Growth*, Springer-Verlag, New York.

Smil, V., 1994, *Energy in World History*, Westview, Boulder.

Vasey, D.E., 1992, *An Ecological History of Agriculture: 10,000B.C.-A.D. 10,000*, Iowa State, Ames IA.

Nakicenovic, N. and Gruebler, A. eds., 1991, *Diffusion of Technologies and Social Behavior*, International Institute for Applied Systems Analysis, Springler-Verlag, Berlin.

Gruebler, A., 1989, *The Rise and Fall of Infrastructures: Dynamic Evolution and Technological Change in transport*, Physica-Verlag, Heidelberg, Germany.

Ausubel, J.H., 1988, Regularities in Technological Development: An Environmental View, pp. 70-94 in *Technology and Environment*, Ausubel, J.H. and Sladovich, H.E., eds., National Academy Press, Washington, D.C.

International Comparisons

Erkman, Suren, 1995, *Ecologie Industrielle, Metabolisme Industriel, et Socie'te' D'utilisation*, Supported by the Foundation for the Progress of Humanity, Paris.

Fishbein, B.K, 1994, *Germany, Garbage, and the Green Dot*, INFORM, New York.

Overcash, M.R., 1994, Cleaner Technology Life Cycle Methods: European Research and Development, *Hazardous Waste & Hazardous Materials* 11(4):459-477

Watanabe, C., 1993, Energy and Environmental Technologies in Sustainable Development: A View From Japan, *The Bridge*, Summer 1993, National Academy of Engineering, Washington D C

Smith, T.T., 1993, *Understanding European Environmental Regulation*, Conference Board Report #1026, Conference Board, New York.

World Bank, 1989, *Environmental Accounting for Sustainable Development: Selected Papers from Joint World Bank Workshops*, World Bank, Washington, D.C.

Hershkowitz, A. and Salerni, E., 1987, *Garbage Management in Japan: Leading the Way*, INFORM, New York.

Hoberg, G. Jr., 1986, Technology, Political Structure, and Social Regulation: A Cross-National Analysis, *Comparative Politics*, 18:357-376.

Choosing the Material

Eisenberger, P., ed., 1996, *Basic Research Needs for Environmentally Responsive Technologies of the Future*, Princeton Materials Institute, Princeton, NJ.

US Congress Office of Technology Assessment, 1993, *Biopolymers: Making Materials Natures Way*, OTA Report no. OTA-BP-E-102, Washington, D.C.

Allenby, B.R., 1992, Industrial Ecology: The Materials Scientist in an Environmentally Constrained World, *Materials Research Bulletin* (17)3:46-51.

Douglas, J.M., 1992, Process Synthesis for Waste Minimization, *Industrial & Engineering Chemistry Research*, v. 31 no. 238.

Mitchell, J.W., 1992, Alternative Starting Materials for Industrial Processes, *Proceedings of the National Academy of Sciences of the USA* 89(3):821-826.

National Academy of Sciences, 1989, *Materials Science and Engineering for the 1990s*, National Academy Press, Washington, D.C.

Ashby, M.F., 1979, The Science of Engineering Materials, pp. 19-48 in *Science and Future Choice*, Hemily, P.W. and Özdas, M.N., eds., North Atlantic Treaty Organization, Clarendon Press, Oxford, U.K.

Designing the Product

U.S. Congress Office of Technology Assessment, 1992, *Green Products by Design: Choices for a CLeaner Environment,* OTA-E-541, U.S. Government Printing Office, Washington, D.C.

Overby, C., 1990, *Design for the Entire Life Cycle: A New Paradigm*, 1990 ASEE Annual Conference Proceedings, Industrial & Systems Engineering Dept., Ohio University, Athens, OH

Recovering the Material

Barsotti, A.F. and Kalyoncu, R., 1995, *Implications of Flue Gas Desulfurization on the Mineral Industries*, Available from Minerals Information Office, U.S. Geological Survey, Reston, VA.

Council for Agricultural Science and Technology, 1995, *Waste Management and Utilization in Food Production and Processing,* CAST, Ames, IA.

Philbin, M.L., 1995, Sand Reclamation 1995: Is it Time for Your Foundry?, *Modern Casting* 85:25-9.

Allen, D.T. and Behamanesh, N., 1994, Wastes as Raw Materials, pp. 68-96 in *The Greening of Industrial Ecosystems*, Allenby, B.R. and Richards, D.J., eds., National Academy Press, Washington, D.C.

Lave, L., Hendrickson, C.T., and McMichael, F.C., 1994, Rethinking How We Recycle, *Environmental Science and Technology* 28(1):19A-24A.

Hager, J.P., et al., eds., 1994, *Extraction and Processing for the Treatment and Minimization of Wastes,* The Minerals, Metals, and Materials Society, Warrendale, PA.

Ahmed, I., 1993, *Use of Waste Materials in Highway Construction*, Noyes Data Corporation, Park Ridge, NJ.

Butterwick, L. and Smith, G.D.W., 1986, Aluminum Recovery from Consumer Waste: Technology review, *Conservation & Recycling* 9(3):281-92.

Markets and Information

Frosch, R.A., 1996, Toward the End of Waste: Reflections on a New Ecology for Industry, *Daedalus* 125(3):199-212.

USEPA, 1994, *Review of Industrial Waste Exchanges,* EPA Report no. EPA-530-K-94-003, Waste Minimization Branch, Office of Solid Waste, USEPA, Washington, D.C.

Beckerman, W., 1992, *Pricing for Pollution: An Analysis of Market Pricing and Government Regulation in Environment Consumption and Policy*, Institute for Economic Affairs, London, U.K.

JETRO (Japan External Trade Organization), 1992, Ecofactory-Concept and R&D Themes, special issue of *New Technology,* FY 1992, Ecofactory Research Group, Agency of Industrial Science and Technology, Tokyo, Japan.

Page, T., 1977, *Conservation and Economic Efficiency: An Approach to Materials Policy,* Published for Resources for the Future by the Johns Hopkins University Press, Baltimore, MD.

Business and Finance

Richards, D.J., ed., *The Industrial Green Game: Implications for Environmental Design and Management,* National Academy of Engineering, National Academy Press, Washington, D.C., in press.

Allenby, B.R., Evolution of the Private Firm in an Environmentally Constrained World, in *The Industrial Green Game: Implications for Environmental Design and Management*, D.J. Richards, ed., National Academy Press, Washington, D.C., in press.

Battelle Pacific Northwest Laboratory, 1996, *The Source of Value: An Executive Briefing and Sourcebook on Industrial Ecology*, Prepared for the Future Studies Unit, Office of Policy, Planning, and Evaluation, U.S. Environmental Protection Agency by Battelle, Pacific Northwes Laboratory, Richland, WA.

Fiksel, J., ed., 1996, *Design for Environment: Creating Eco-Efficient Products and Processes*, McGraw-Hill, New York.

Guile, B.R. and Cohon, J.L., 1996, Services and the Environment: More Questions Than Answers, Available from the National Academy of Engineering, Washington, D.C.

Bravo, C.E., 1995, A View of the United States Postal Service as a Service Sector Corporation presented at the Fourth Annual National Academy of Engineering Workshop on Industrial Ecology, July 5-7, Woods, Hole, MA.

Ditz, D., Ranganathan, J., and Banks, R.D., 1995, *Green Ledgers: Case Studies in Corporate Enronmental Accounting*, World Resources Institute, Washington D.C.

Porter, M.E. and van der Linde, C., 1995, Green and Competitive: Ending the Stalemate, *Harvar Business Review*, September-October 1995, pp. 122-134.

Porter, M.E. and van der Linde, C., 1995, Toward a New Conception of the Environment-Competitiveness Relationship, *Journal of Economic Perspectives* 9(4).

Rejeski, D., 1995, The Forgotten Dimensions of Sustainable Development: Organizational Learning and Change, *Corporate Environmental Strategy*, 3(1):19-29.

National Academy of Engineering, 1994, *Corporate Environmental Practices: Climbing the Learning Curve*, National Academy Press, Washington, D.C.

Romm, J.J., 1994, *Lean and Clean Management: How to Boost Profits and Productivity by Reducing Pollution*, Kodansha America, New York.

Walley, N. and Whitehead, B., 1994, It's Not Easy Being Green, *Harvard Business Review* M June 1994 pp. 46-52.

3M Corporation, 1993, *3M Waste Minimization Guidelines*, 3M Corporation, St. Paul, MN.

3M Corporation, 1982, *Low- or Non-Pollution Technology Through Pollution Prevention: An Overview*, 3M Corporation, St. Paul, MN.

Regulation and Law

Allenby, B.R. and Graedel, T.E., 1996, *The Policy Implications of Industrial Ecology*.

Andrews, C., 1994, Policies to Encourage Clean Technology, pp. 405-423 in *Industrial Ecology and Global Change*, Socolow, R., Andrews, C., Berkhout, F., and Thomas V., eds , Cambridge University Press, New York.

U S. Congress, Office of Technology Assessment, 1995, *Environmental Policy Tools: A User's Guide*, OTA Report no. OTA-ENV-634, US GPO, DC.

Portney, P, (ed.), 1990, *Public Policies for Environmental Protection*, Resources for the Future, Washington, DC.

Vig, N.J. and Kraft, M.E., 1990, *Environmental Policy in the 1990s*, Congressional Quarterly Inc, Washington, DC.

Lester, J P., 1989, *Environmental Politics and Policy*, Duke University Press, Durham, NC.

Rejeski, D , 1996, Clean Production and the Command-and-Control Paradigm, in *Environmental Management Systems and Cleaner Production*, John Wiley and Sons, New York.

Hodges, C.A., 1995, Mineral Resources, Environmental Issues, and Land Use, *Science* 268 1305-12.

Wilt, C. and Davis, G , 1995, *Extended Producer Responsibility: A New Principle for a New Generation of Pollution Prevention*, Proceedings of the Symposium on Extended Producer Responsibility, Washington, D.C., Nov. 14-15, 1995.

Esty, D C , 1994, *Greening the GATT: Trade, Environment, and the Future*, Institute for International Economics, Washington, D.C.

National Academy of Engineering, 1994, *Industrial Ecology: US/Japan perspectives*, National Academy Press, Washington, D.C.

Lifset R., 1993, Take it Back: Extended Producer Responsibility as a Form of Incentive-Based Environmental Policy, *Journal of Resource Management and Technology*, 21(4):163-175

President's Commission on Environmental Quality, Deland, M.R., Chairman, 1993, *Partnerships to Progress. The Report of the President's Commission on Environmental Quality*, Executive Office of the President, Washington D.C.

President's Commission on Environmental Quality, Derr, K.T., Chairman, 1993, *Total Quality Management: A Framework for Pollution Prevention*, Executive Office of the President, Washington D.C.

MacDonald, G.J., 1989, *Policies and Technologies for Waste Reduction and Energy Efficiency*, MITRE Corporation, McLean, VA.

Regional Strategies

Lowe, E., et al., 1995, *Fieldbook for the Development of Eco-Industrial Parks V. II*, Final Report, Indigo Development, Research Triangle Institute Project Number 6050, Research Triangle Park, NC.

Cote', R., et al., 1994, *Designing and Operating Industrial Parks as Ecosystems*, School for Resource and Environmental Studies, Faculty of Management, Dalhousie University, Halifax, Nova Scotia B3J 1B9.

Technology Studies (General and Specific)

General

AT&T Technical Journal, November December 1995, Volume 74, Number 6, Special Issue-AT&T Technology and the Environment.

Fresenius Environmental Bulletin, 1993, Special issue on materials, 2(8):407-490

Specific

Swan, C., 1996, *Transportation Transformation*, Ten Speed Press, Berkeley, CA

Lovins, A B , Barnett, J.W , and Lovins, L.H., 1995, *Supercars. The Coming Light-Vehicle Revolution*, Rocky Mountain Institute, Snowmass, CO.

Microelectronics and Computer Technology Corporation, 1993, *Environmental Consciousness: A Strategic Competitiveness Issue for the Electronics and Computer Industry*, The Microelectronics and Computer Technology Corporation, Austin, TX.

Overcash, M.R., 1993, Net Waste Reduction Analysis Applied to Air Pollution Control Technologies, *Journal of the Air & Waste Management Association* 43:1449-1554

INFORM, 1992, *Environmental Dividends: Cutting More Chemical Wastes*, Dorfman, M.H., Muir, W R., and Miller, C.G., eds , INFORM, New York.

Douglas, J.M. , 1988, *Conceptual Design of Chemical Processes*, McGraw-Hill, New York, N

Fathi-Afshar, S. and Yang, J.C., 1985, The Optimal Structure of the Petrochemical Industry for Minimum Cost and Least Gross Toxicity of Chemical Production, *Chemical Engineering Science* 40, 781.

INFORM, 1985, *Cutting Chemical Wastes*, INFORM, New York.

Overcash, M.R., 1985, Land Treatment of Wastes: Concepts and General Design, *Journal of Environmental Engineering* 111:141-160

Wastes (General)

General

Gottlieb, R., ed., 1995, *Reducing Toxics*, Island Press, Washington, D.C.

Rathje, W. and Murphy, C., 1992, *Rubbish,* Harper Collins, New York.

U.S. Congress, Office of Technology Assessment, 1992, *From Pollution to Prevention: A Progress Report on Waste Reduction,* OTA Report no. OTA-ITE-347, U.S. Government Printing Office, Washington, D.C.

U.S. Congress, Office of Technology Assessment, 1986, *Serious Reduction of Hazardous Waste for Pollution Prevention and Industrial Efficiency*, OTA Report no. OTA-ITE-317, U.S. Government Printing Office, Washington, D.C.

Consumers

Wernick, I.K., 1996, Consuming Materials: The American Way, *Technological Forecasting and Social Change*, 53(1).

Lebergott, S., 1993, *Pursuing Happiness: American Consumers in the Twentieth Century*, Princeton University Press, Princeton, NJ.

Durning, A., 1992, *How Much is Enough? The Consumer Society and the Future of the Earth*, W.W. Norton & Company, New York.

Uusitalo, L., 1986, *Environmental Impacts of Consumption Patterns*, St. Albans Press, New York.

Global Issues

Socolow, R., Andrews, C., Berkhout, F., and Thomas V., eds., 1994, *Industrial Ecology and Global Change,* Cambridge University Press, New York.

Waggoner, P.E., 1994, *How Much Land Can Ten Billion People Spare for Nature,* Council for Agricultural Science and Technology, Task Force Report no. 121, Ames, IA.

Ayres, R.U., 1992, Toxic Heavy Metals: Materials Cycle Optimization, *Proceedings of the National Academy of Sciences of the USA* 89(3):815-20, National Academy Press, Washington, D.C.

Forrest, D. and Szekely, J., 1991, Global Warming and the Primary Metals Industry, *Journal of the Minerals, Metals, and Materials Society*, 43(12):23-30.

General

Barsotti, A.F., 1994, *Industrial Minerals and Sustainable Development*, U.S. Bureau of Mines, Division of Minerals Commodities, Branch of Industrial Minerals, Washington, D.C.

Sawyer, D.T. and Martell, A.E., eds., 1992, *Industrial Environmental Chemistry,* Plenum Press, New York.

Hirschhorn, J.S., 1991, *Prosperity Without Pollution: The Prevention Strategy for Industry and Consumers*, Van Nostrand Reinhold, New York.

National Academy of Sciences, 1991, Industrial Ecology, Proceedings from NAS colloquium on industrial ecology held May 20-21, 1991, Washington, D.C.

VI. JOURNALS, DATA SOURCES, AND WEB RESOURCES

Journals

Environmental Science & Technology, Glaze, W. ed , American Chemical society
Journal Homepage: http://acsinfo.acs.org/hotartcl/est/est.html

International Journal of Environmentally Conscious Manufacturing, Jeff Weinrach, ed., POB 20959, Albuquerque NM.

Journal of Hazardous Materials, G. F. Bennett, ed., Dept. of Chemical Engineering, University of Toledo, 2801 West Bancroft, Toledo OH 43606

Journal of Industrial Ecology, Quarterly, Lifset, R., ed., MIT Press.
Journal homepage: http://www-mitpress.mit.edu/jrnls-catalog/indus-ecol.html

Journal of Cleaner Production, , Huisingh, D., ed., Elsevier Science
Journal homepage: http://webhost1.cerf.net/cas/estoc/contents/SAG/09596526.html,

Science of the Total Environment, Weekly, Nriagu, J.O., ed., Elsevier Science
Journal homepage: http://www.elsevier.com/locate/estoc

Scrap Recycling and Processing, Institute of Scrap Recycling Industries, A bi-monthly trade journal for the scrap reprocessing industry. Homepage:
http://www.isri.org/pubcat00.htm#scrapmag

Selected Data Sources (General and Specific)

General

Organization for Economic Cooperation and Development (OECD), 1994, *Environmental Indicators*, Paris, France.

U S Bureau of the Census, 1975, *Historical Statistics of the United States, Colonial Times to 1970*, U S. Government Printing Office, Washington, D.C.

U S Bureau of the Census, Annual editions, *Statistical Abstract of the United States*, U.S. Government Printing Office, Washington, D.C.

Council on Environmental Quality, Annual editions, *Environmental Quality*, U.S. Government Printing Office, Washington, D.C.

Specific

INFORM, 1995, *Toxics Watch 1995*, INFORM, New York.

Allen, D.T. and Jain, R.K., eds., 1992, Special Issue on National Hazardous Waste Databases, *Hazardous Waste & Hazardous Materials* 9(1):1-111.

American Petroleum Institute, 1992, *Generation and Management of Wastes and Secondary Materials: Petroleum Refining Performance 1989 survey,* API, Washington, D.C.

U.S. Congress, Office of Technology Assessment, 1992, *Managing Industrial Solid Wastes fr Manufacturing, Mining, Oil and Gas Production, and Utility Coal Combustion,* OTA Report OTA-BP-O-82, U.S. Government Printing Office, Washington, D.C.

U.S. Environmental Protection Agency, 1992, *Characterization of Municipal Solid Waste in the United States: 1992 Update, Final Report,* EPA Report no. 530-R-92-019, USEPA, Washington D.C.

U.S. Bureau of Mines, 1991, *Minerals Yearbook 1991,* U.S. Government Printing Office, Washington, D.C.

Franklin, W.E., and Associates, 1990, *Paper Recycling: The View to 1995, Summary Report,* Prepared for the American Paper Institute Feb. 1990, Prairie Village, KS.

U.S. Environmental Protection Agency, 1990, *Report to Congress on Special Wastes from Mineral Processing, Summary and Findings, Methods and Analysis,* EPA Report no. 570-SW-90-070C, USEPA, Washington, D.C.

U S. Environmental Protection Agency, 1988, *Report to Congress: Solid Waste Disposal in the Unites States*, Vols. 1-2, EPA Report no. EPA/530-SW-89-033A, USEPA, Washington, D.C

U.S. Environmental Protection Agency, 1986, *Waste Minimization: Issues and Options,* EPA Report no. 530-SW-86-04, USEPA, Washington, D.C.

Chemical Manufacturers Association, Annual editions, *United States Chemical Industry Statistical Handbook*, Chemical Manufacturers Association, Washington, D.C.

U.S. Bureau of Mines, Annual editions, *Mineral Commodity Summaries*, U.S. Government Printing Office, Washington, D.C.

U.S. Bureau of Mines, Annual editions, *Mineral Facts and Problems*, U.S. Government Printing Office, Washington, D. C.

Wards Automotive Yearbook, Annual editions, Wards Communications. Detroit, MI.

Web site list

Center for Clean Technology (CCT) at UCLA
http://cct.seas.ucla.edu/cct.pp.html

Global Recycling Network
http://grn.com/grn/ora.html

National Materials Exchange Network
http://www.earthcycle.com/nmen

IEEE white papers on sustainable development and industrial ecology
http://www.ieee.org/ehs/ehswp.html

USEPA Homepage
http://www.epa.gov

Program for the Human Environment, Rockefeller University
http://phe.rockefeller.edu

World Resources Institute (databases)
http://www.wri.org/wri/

National Pollution Prevention Center for Higher Education at the University of Michigan
http://www.umich.edu/~nppcpub/ind.ecol.html

The Technology, Business and Environment Program at the Massachusetts Institute of Technology
http://web.mit.edu/ctpid/www/tbe

The Department of Energy Pollution Prevention Clearinghouse
http://146.138.5.107/epic.html

The Department of Energy Efficiency and Renewable Energy Network (EREN)
http://www.eren.doe.gov

Oak Ridge National Laboratory CADDET (Database of demonstration projects on energy efficient and renewable energy technologies)
http://www.ornl.gov/CADDET

Center for Green Design and Manufacturing (UC Berkeley)
http://euler.berkeley.edu/green/cgdm.html

VII. BIOGRAPHICAL INFORMATION

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Jesse H. Ausubel directs the Program for the Human Environment at The Rockefeller University in New York City, where he has led a series of studies exploring how technology can spare demand for materials, energy, land, and other resources.

Robert U. Ayres is Sandoz Professor of Management and the Environment at the European Institute of Business Administration (INSEAD) near Paris. Dr. Ayres has pioneered studies of marterials flows, especially of heavy metals.

R. Darryl Banks directs the program for Technology and the Environment at the World Resources Institute in Washington DC, having served earlier as one of New York State's top environmental officials. His recent work has included studies of improving methods for corporate environmental accounting.

Faye Duchin is Dean of the School of Humanities and Social Sciences at Rensselaer Polytechnic Institute. An economist, Prof. Duchin has developed numerous applications of input-output modeling, including to issues of environmentally sound development, in the United States as well as developing countries.

John R. Ehrenfeld directs the Program on Technology Business & Environment at the Center for Technology Policy & Industrial Development at the Massachusetts Institute of Technology. Dr. Ehrenfeld's research focuses on the way businesses manage environmental concerns and implement organizational and technological changes to improve their environmental performance.

Peter Eisenberger directs the Earth Institute as well as the Lamont Doherty Earth Observatory, both at Columbia University. Formerly, Dr. Eisenberger headed the Princeton Materials Institute and worked as an industrial research physicist investigating the properties of materials

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Bruce R. Guile is managing director of the Washington Advisory Group, a consultancy specializing in management of technology and research. From 1989-1995, Dr. Guile served as director of programs for the National Academy of Engineering. He edits the policy perspectives section of the Journal of Industrial Ecology.

Reid Lifset is Associate Director of the Industrial Environmental Management Program at the Yale School of Forestry & Environmental Studies and editor of the *Journal of Industrial Ecology*. His research focuses on the application of industrial ecology and policy analysis to solid waste problems in the United States.

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Iddo Wernick is a Research Associate in the Program for the Human Environment at The Rockefeller University and a Research Scientist with Columbia's Earth Institute. A physicist by training, Dr. Wernick's research has focused on materials production and usage in the United States.

Figure Captions

Figure 1. Chlorine process-product flows for Western Europe 1992 (kMT Chlorine content). The figure (left to right) indicates the processes and quantities involved in chlorine chemical production. The figure demonstrates that even large and complex materials flow streams such a those for chlorine can be successfully tracked and accounted for, thus indicating where system losses occur. Rectangles refer top chemical processes for conversion and circles refer to products. Source: Ayres, R.U. and Ayres, L.W., The Life-Cycle of Chlorine: Part I-IV, *Journal c Industrial Ecology*, in press.

Figure 2. The spaghetti diagram indicates the flows of metals among a sample of metals processors in New England. The arrows indicate the direction of the flow, while the number of lines indicate the magnitude. Note the presence of waste reclaimers, dismantlers, and scrap dealers that allow for system closure. Source: Frosch, R.A., Clark, W.C., Crawford, J., Tschang T.T., and Weber, A., 1996, The Industrial Ecology of Metals: A reconnaissance, From a talk delivered at the Royal Society/Royal Academy of Engineering meeting, May 29-30, London, U.K.

Figure 3. Material flows in the US forest products industry, 1993. Box heights are to scale. All values in million cubic meters. For paper we consider one metric ton to be equivalent to two cubic meters. a) Based on the ratio of logging residues (15.1%) and 'Other Removals' (6.6%) to all removals for 1991. b) The dashed lined entering paper represents the inputs from "recycled" We estimate that 100 million cubic meters of the woody mass entering paper mills undergoes combustion for energy. In 1991 the paper industry (SIC 26) generated over 1.2 quadrillion Btu from pulping liquors, chips, and bark. c) Construction includes millwork such as cabinetry and moldings. 'Other' includes industrial uses such as materials handling, furniture, and transport. d) The ratio of end uses relies on Btu data from the USDOE Energy Information Administration The category 'Residential and Commercial' includes Electric Utilities. Sources: Ince 1994; Energy Information Administration 1994; U.S. Department of Agriculture 1993; U.S. Bureau of the Census 1995; Amer. Forest & Paper Assoc., 1995; Smith et. al. 1994; and data from the Engineered Wood Products Assoc., Tacoma WA. and the Western Wood Products Assoc., Portland, OR.

Figure 4. This figure shows world cadmium consumption by end use. Source: Cadmium Market Update Analysis and Outlook, Roskill Information Services Ltd., 1995, London.

Figure 5. T.K. Sherwood empirically identified a relationship between the selling prices of materials and their dilution (or degree of distribution in the initial matrix from which they are separated). The diagonal line denotes this empirically observed linear relationship. The data points indicate the minimum concentration of metals wastes typically recycled as a function of metal price. Points lying above the line indicate the existence of metals in wastes typically not recycled even though their concentration exceeds those found in virgin ores. Source: Allen, D. and Behamanesh, N., 1994, Wastes as Raw Materials, pp. 68-96 in *The Greening of Industrial*

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Figure 6. A schematic diagram of the industrial ecopark located in Kalundborg, Denmark. The figure shows the industrial concerns that occupy the park, the materials and energy flows between them, and the nature and fate of outgoing material and energy streams. After Allenby, B.R. and Graedel, T.E., 1994, Defining the Environmentally Responsible Facility, AT&T, Murray Hill, NJ.

Figure 1.
Chlorine process-product flows for Western Europe 1992

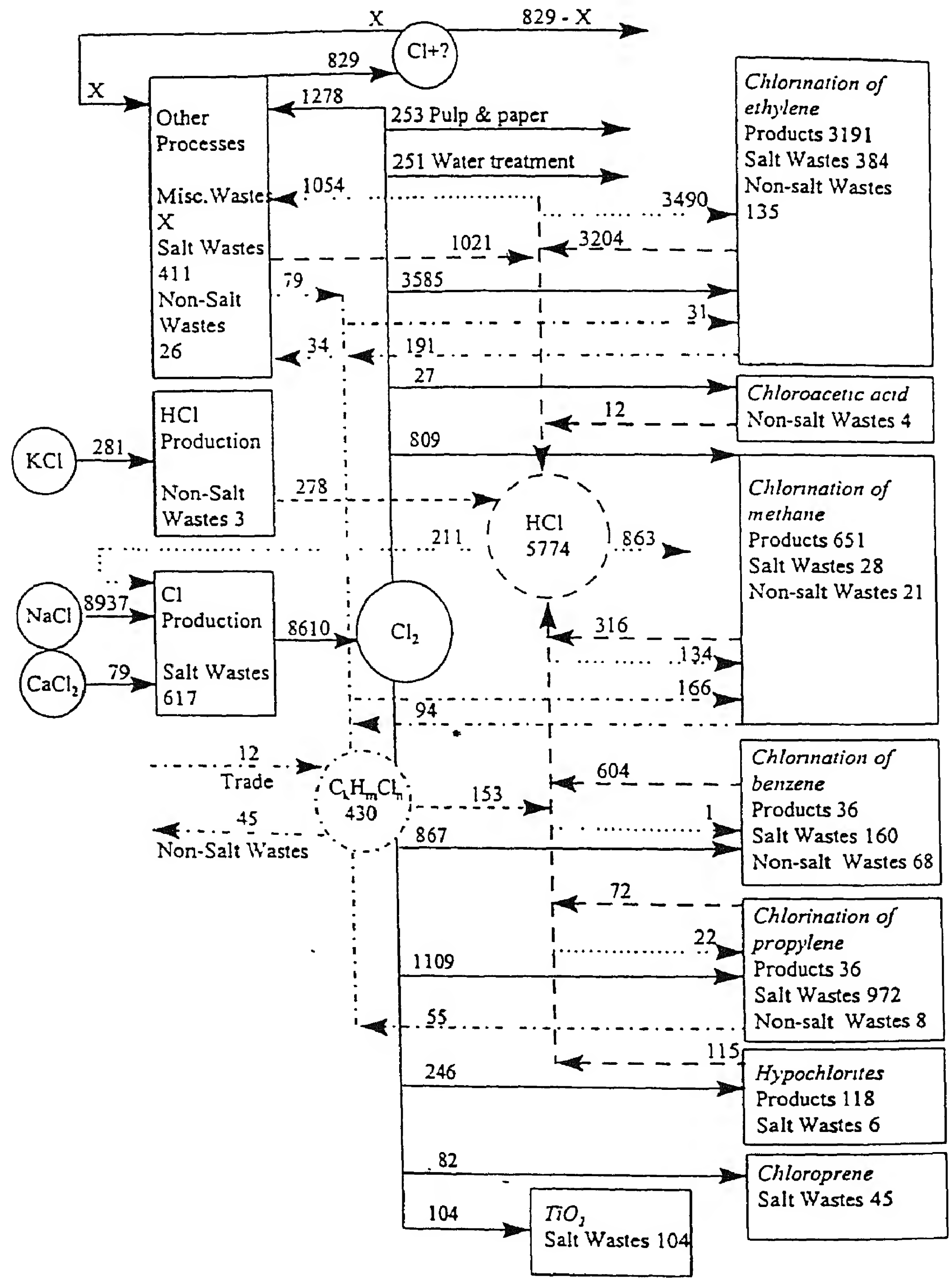


Figure 1. Chlorine process-product flows for Western Europe 1992 (kMT Chlorine content). The figure (left to right) indicates the processes and quantities involved in chlorine chemical productio The figure demonstrates that even large and complex materials flow streams such as those for chlorine can be successfully tracked and accounted for, thus indicating where system losses occur Rectangles refer top chemical processes for conversion and circles refer to products. Source: Ayre R.U. and Ayres, L.W., The Life-Cycle of Chlorine: Part I-IV, *Journal of Industrial Ecology*, in pre

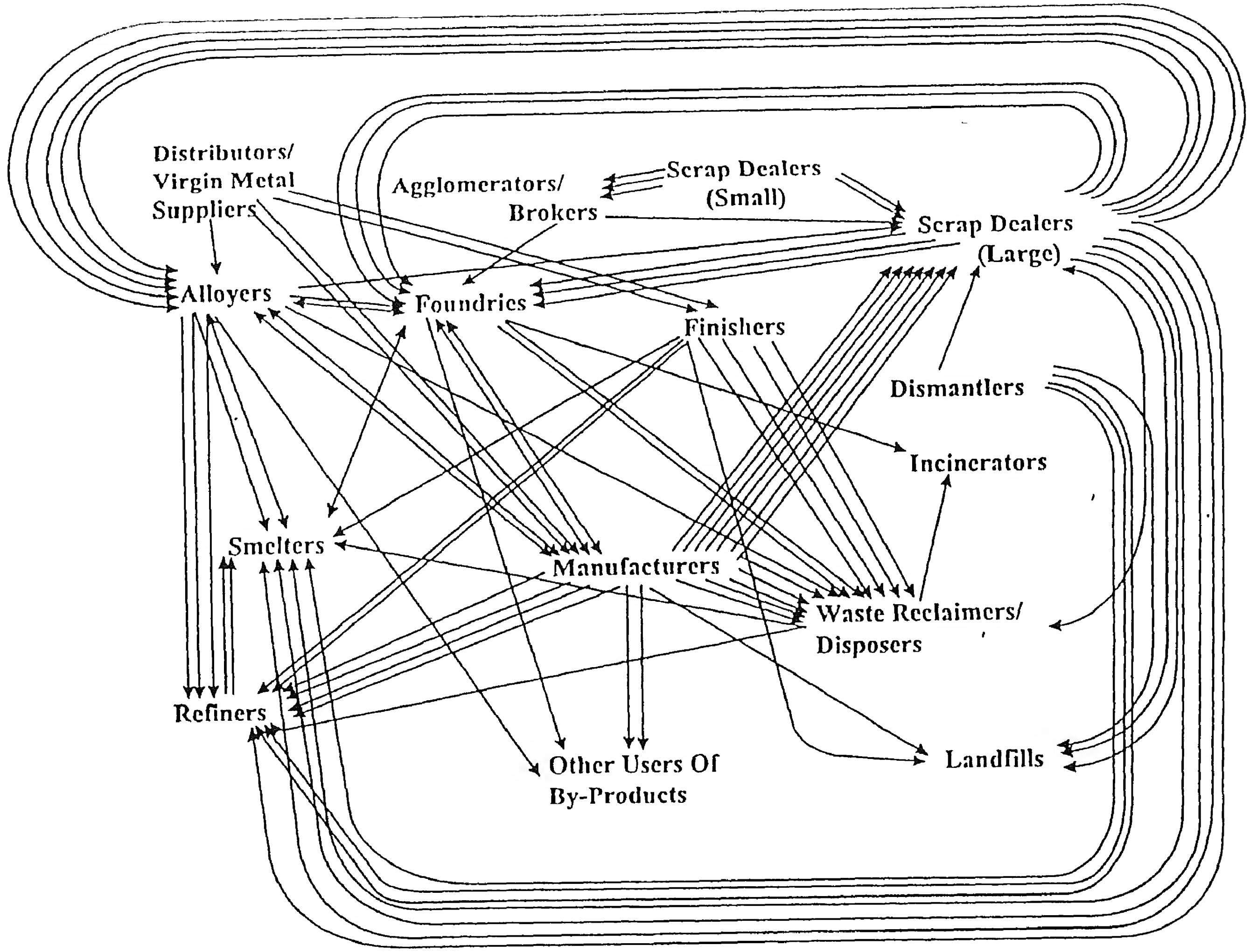
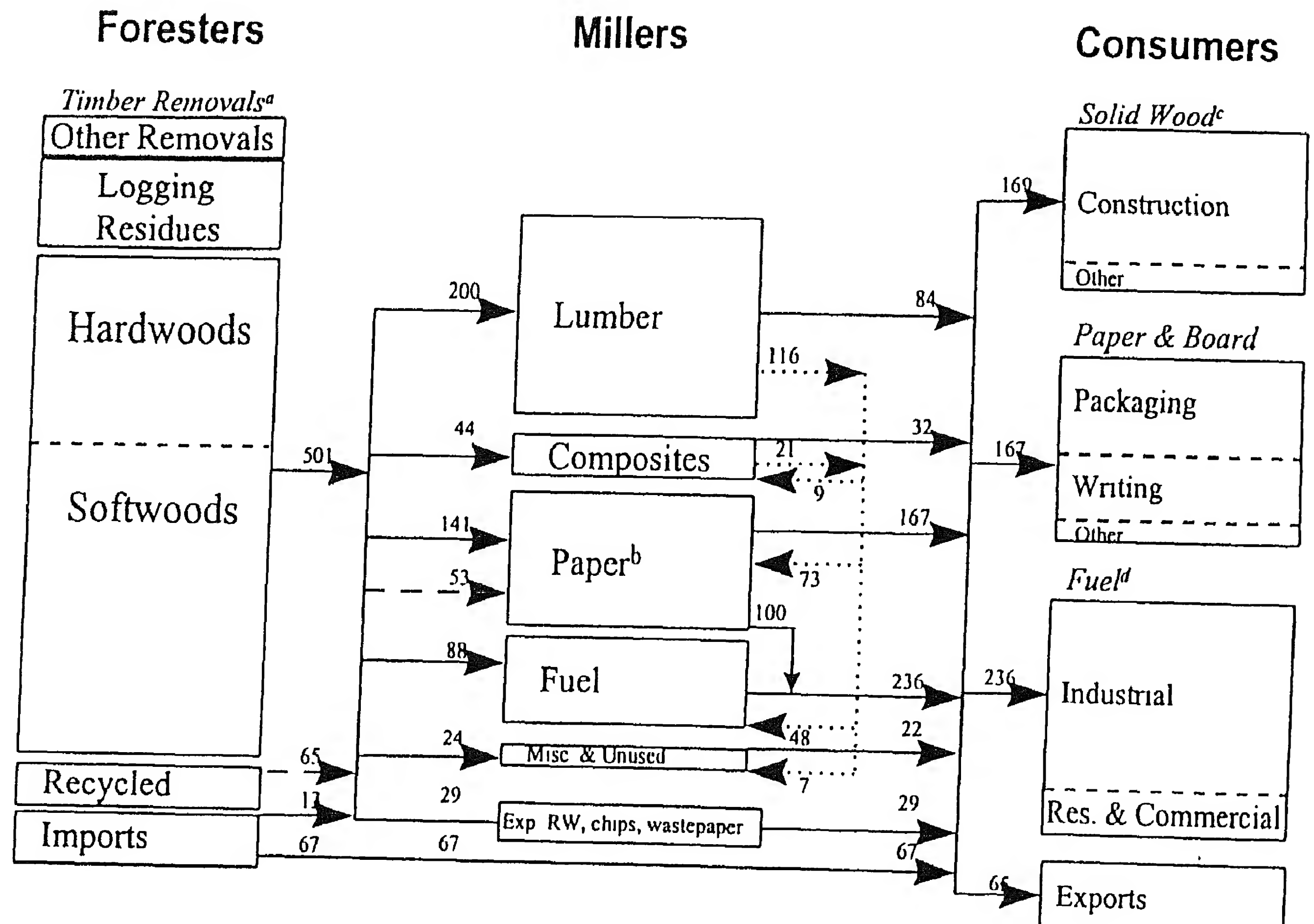


Figure 2. The spaghetti diagram indicates the flows of metals among a sample of metals processors in New England. The arrows indicate the direction of the flow, while the number of lines indicate the magnitude. Note the presence of waste reclaimers, dismantlers, and scrap dealers that allow for system closure. Source: Frosch, R.A., Clark, W.C., Crawford, J., Tschang, T.T., and Weber, A., 1996, The Industrial Ecology of Metals: A reconnaissance, From a talk delivered at the Royal Society/Royal Academy of Engineering meeting, May 29-30, London, U.K.

Figure 3. Material Flows in the U.S. Forests Products Industry, 1993.



Box Heights Are To Scale. All Values in Million Cubic Meters.

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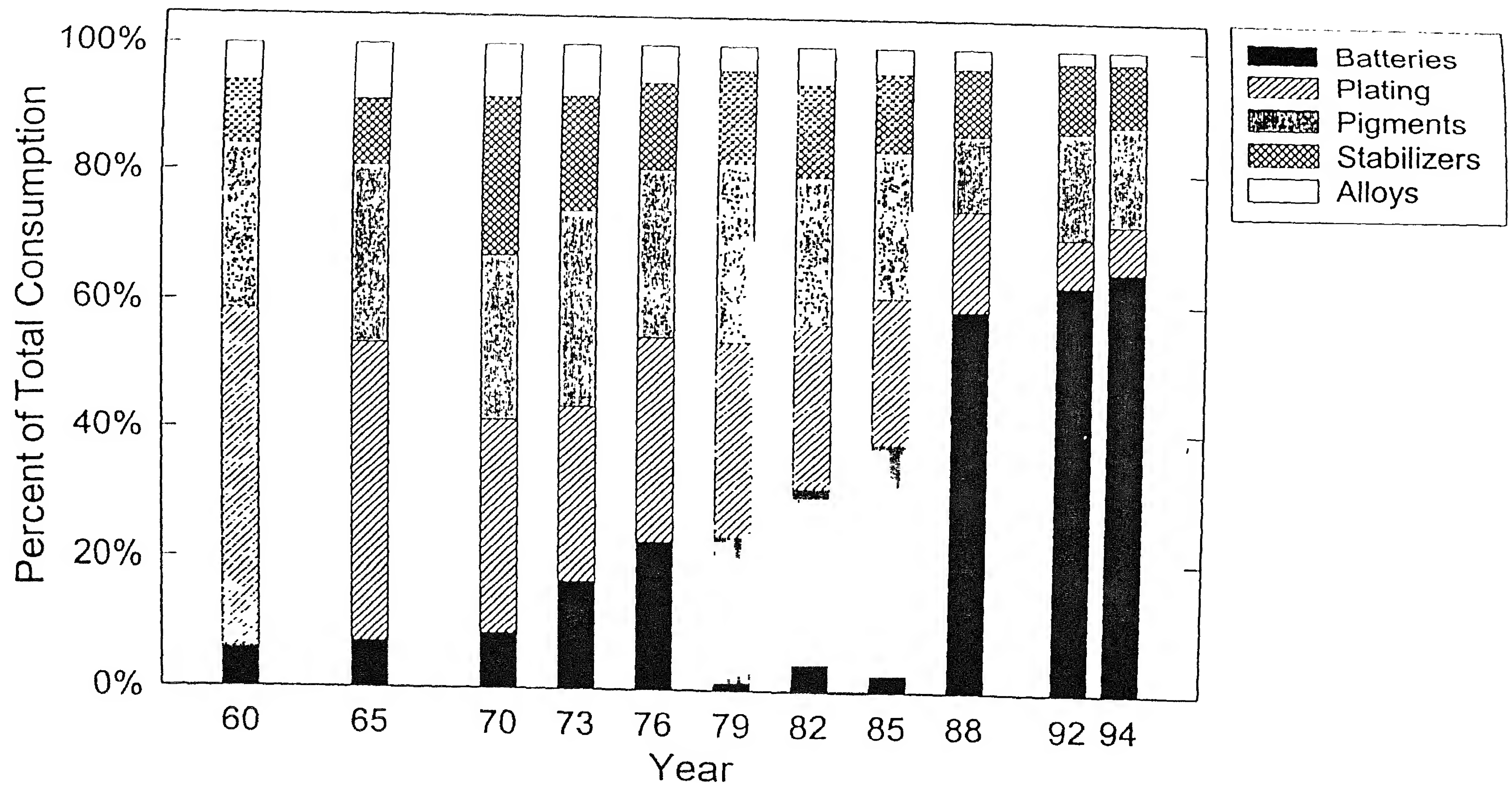
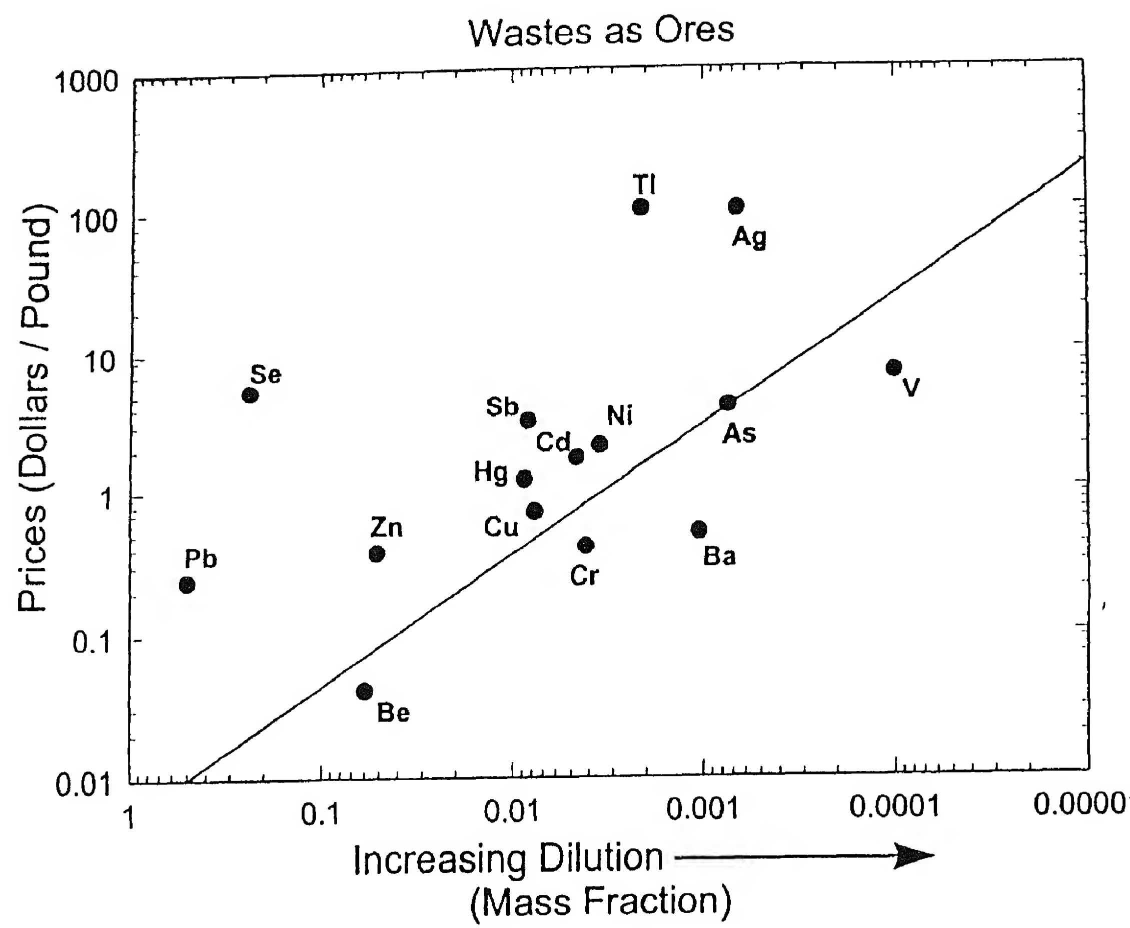


Source of Data: Cadmium: Market Update, Analysis and Outlook, Roskill Information Services Ltd., London, 1995.

Figure 5. Sherwood Plot of Price vs. Dilution of Materials



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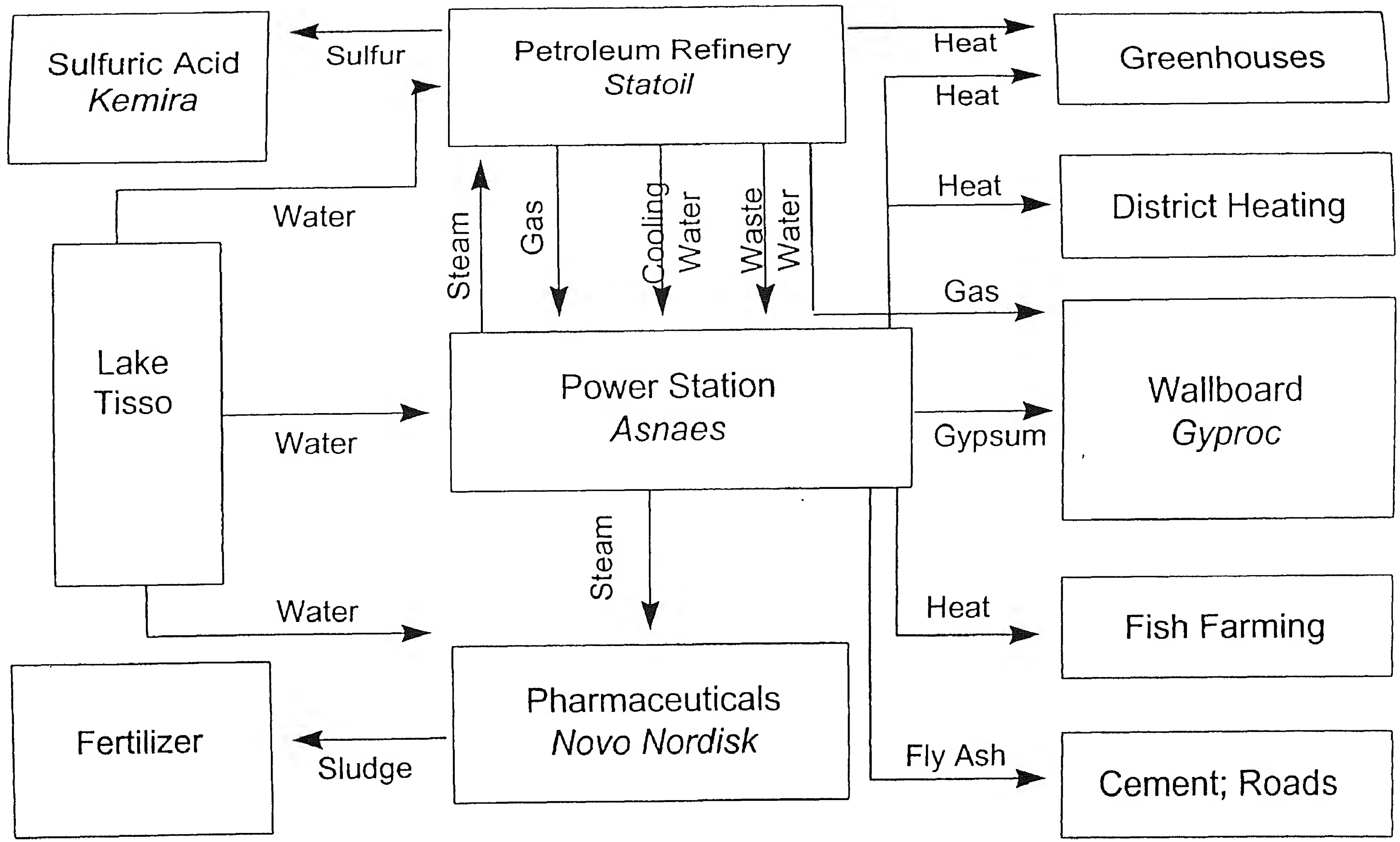
Symbiosis of industrial facilities: The Kalundborg ecopark



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[Draft, 1 April 1998]

INDUSTRIAL TRANSFORMATION IN ASIA - EMERGING ISSUES FOR FURTHER RESEARCH

Background paper prepared for the Regional Workshop on Research Agenda for International Human Dimensions of Global Environmental Change Programme - Industrial Transformation (IHDP-IT), April 4-5, 1998, New Delhi

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Industrial Transformation in Asia - Emerging Issues for Further Research

1.0 Introduction

Over the years, it has become apparent that the major task before us is to achieve a balance between environmental protection and industrial development. The long-term prospects for industrialization and development in the developing countries to the current levels of affluence in the industrial world are clouded by the untenability of the resource and pollution burden it will impose on the planet's ecosystem. In the immediate term (say a couple of decades), however, there appears to be considerable scope for incorporating an accelerated introduction of energy efficiency and cleaner technologies as an integral part of the development process. Therefore, there is a great need for realizing this potential and acting accordingly to help orient the development in an environmentally friendly manner. Problems relating to economy, pollution and consumer needs arise while accomplishing these. A great deal of effort, in terms of research, planning and implementation, in a well coordinated manner need to be put in so as to shape the process of industrial development with least impacts on the global environment.

The International Human Dimensions of Global Environmental Change Programme (IHDP), Germany, initiated in 1990 by the International Social Science Council, fosters research-related activities that seek to describe and understand the human role in causing global environmental change and the consequences of these changes for society. Industrial Transformation (IT) has been identified as one of the six priority research topics within IHDP. The ultimate aim of IHDP-IT is to understand the human drives and mechanisms that could enable a transformation of the industrial system towards sustainability and, in physical terms, to de-couple industrial activities from their environmental impacts

Industrial Transformation encompasses all research efforts related to describing the patterns (over space and time), organization and technology of production and consumption of manufactured goods and services, their material and energy transformations and associated environmental impacts, and the consequences of these impacts for the quality of life.

However, the need to prioritize the most pressing issues that highly influence the environmental conditions and development cannot be over emphasized in the process of prioritizing efforts towards industrial transformation.

2.0 Energy in South Asia and the emerging environmental issues

The most important and abundant source of energy in the Asia and Pacific Region is coal followed by fuel wood and natural gas. Power is another major input to industry and development

To fuel the rapid growth of Asian economies, electricity generation in the region is forecast to grow at an annual rate of 6.5 percent up to the year 2000 and at an annual rate of 5.3 percent between 2000 and 2010. Coal combustion is currently the main source of electricity production, and together they account for 80 percent of Asia's coal consumption, which for the region as a whole is some 2 billion tons per year. Coal use will continue to rise

at an annual rate of 3.7 percent per year to reach 3.1 billion tonnes by 2010, because of its abundant availability and cost advantage.

In many Asian countries energy production is inherently inefficient and wasteful due to lack of funds that would enable them to acquire the latest most environmentally-benign technologies as well as inadequacies in the institutional arrangements for energy (particularly the utilities) and energy pricing policies which fail to factor in the true cost of production.

However, coal combustion is the source of many pollutants, including sulphur dioxide, oxides of nitrogen, and dust, and accounts for 80 percent of sulphur dioxide emissions and acid rain in Asia. Whether Asia succeeds in reducing sulphur dioxide emissions and other energy-related pollutants will depend critically on the availability and cost of clean coal technologies.

The selection of coal and its use in the various industrial sectors including power generation for the IHDP-IT programme qualifies because of its significant contribution to global environmental system by way of climate change and resource depletion. The combustion of coal also cause regional global problems that could over time develop into global problems because of acid rains and other human and ecological related problems.

2.1 Coal markets

In an expanded coal-use scenario, potential interregional coal markets exist. Imported coal, despite high transport costs, is generally competitive in some parts of Asia and Southern India. Regions production has not kept pace with consumption despite large coal reserves Thus, South Asian region could be a likely net coal importer.

2.2 Non-CO_2 environmental impacts of coal production and use

Coal has always been an inexpensive fuel in terms of its cost per joule of energy It has also always been an expensive fuel in terms of its associated nonfuel costs, especially its capital costs . In addition, virtually every stage of coal production and use creates by-products, which can adversely affect the environment. These range from gases and particles released into the atmosphere to mine wastes and other discharges. Coal production and consumption processes have coincident environmental hazards, which are associated with virtually every class of environmental degradation The abatement of pollution related to coal use has added significantly to the costs of combustion. Pollution penalties if introduced can be a potential barrier to world coal penetration

2.3 Coal reserves

India is relatively well endowed with both exhaustible and renewable energy sources Coal is the major exhaustible energy resource in the country and has a life expectancy of over 200 years The total coal reserves have been assessed at about 202 billion tonnes (Bt) of which 15% is coking coal and 85% non-coking coal. Of the non-coking coal reserves, 85% is inferior grade (GCV < 5000 Kcal/kg.) mostly suitable only for power generation. 63% of the total coal reserves occur within 300 metres depth in thick interbanded seams and bulk of the reserves are amenable to opencast mining.

2.4 Coal production

Coal industry was nationalized in two stages viz. coking coal mines were taken over in October 1971 and all other coal mines in January 1973. This was done, apart from other considerations, with a view to ensure that the production of coal, which is the primary source of energy, should be properly planned to meet the increasing requirements for the industrial development of the country.

To ensure sustained and planned development of all facets of the coal industry, massive investment to the tune of about Rs 18000 crores has been made since nationalization in opening of new mines, re-organization of existing mines and development of associated infrastructure Coal production has registered an annual growth rate of about 4.3% since nationalization, increasing from a level of 73 Mt in 1970-71 to 270 Mt in 1995-96. In the post-nationalization period, major thrust was given towards development of new outlying coalfields, which contributed 45% of the total coal production in 1995-96. Consequent upon development of new coalfields, a large number of pit-head super thermal power stations have come up. This has helped in reducing the load on railways as most of these pit-head power stations transport their coal by captive modes such as merry-go-round (unit train) system.

The large increases in production could be achieved through enhanced investment in the coal industry by the government, deliberate shift in technology, increased emoluments and welfare amenities for coal workers and other measures. The opencast mines which contributed only about 28% of the total production at the time of nationalization (1973) increased their share to about 72% in 1995-96. The major factors in favour of opencast mines are shorter gestation period, high recovery and safety, and lower cost of production. However bulk of coal produced from opencast mines is inferior grade coal. As a result of this policy, the production of inferior grades of both coking and non-coking coal have been increasing in the last two decades and this trend is continuing.

2.5 Coal consumption trend

The coal consumption has increased from about 72 Mt in 1970-71 to 280 Mt in 1995-96. Electricity sector is the single largest consumer of coal (70%) followed by iron and steel (15%) and cement sectors (4%). The indigenous coal production is by and large meting the country's demand except for the steel sector. The demand of washed coking coal for the steel plants in recent years is far outstripping the indigenous supply both in terms of quality and quantity. The existing washeries are old and are unable to meet the demand in terms of quality of supplies (<17.5% ash content in coal). Therefore, 9 Mt of low ash coking coal is being imported annually by the steel plants for meeting their demand. Cement has emerged as the third largest coal consuming sector. The coal consumption by all other industries was around 10% of the total coal consumption.

2.6 Coal demand

The Working Group for the 9th Plan constituted by the Ministry of Coal, GOI has assessed the coal demand to grow an at average annual rate of 6 %. Based on this, the coal demand for 2011-12 is about 835 Mt. If energy conservation measures are adopted in all the consuming sections, the demand would reduce to 554 Mt in 2011-12 (a TERI estimate)

2.7 Existing technology for coal production

The technology options (opencast or underground mining) is driven by geological, technical and commercial consideration. Opencast mining is almost always cheaper than underground mining. The coal extraction percentage is much higher in opencast mining (90%) as against 30-40% in underground board and pillar mining, which is the most prevalent technology in Indian mines. In addition, while thick seams are a definite advantage in opencast mines, they represent a serious challenge in underground mines. Many thick seams developed on board and pillar method of mining are standing on pillars because of lack of proper technology to extract the pillar. The other advantages of opencast mining include increased safety of operations and lower gestation period. The specific investment per tonne of coal is also comparatively lower than for underground mines.

Coal industry is currently using shovel, dumper, drag line for winning and transportation of coal and overburden. In lignite mines, Bucket wheel excavator, cross pit and around the pit conveying system, and stacker/reclaimer are used for continuous excavation and transportation of lignite and overburden. Present environment management practices in coal mines are backfilling, compaction by shovel dozer for overburden dump, water spraying for dust suppression, and settling tank for water treatment.

2.8 Resource requirements for the coal cycle

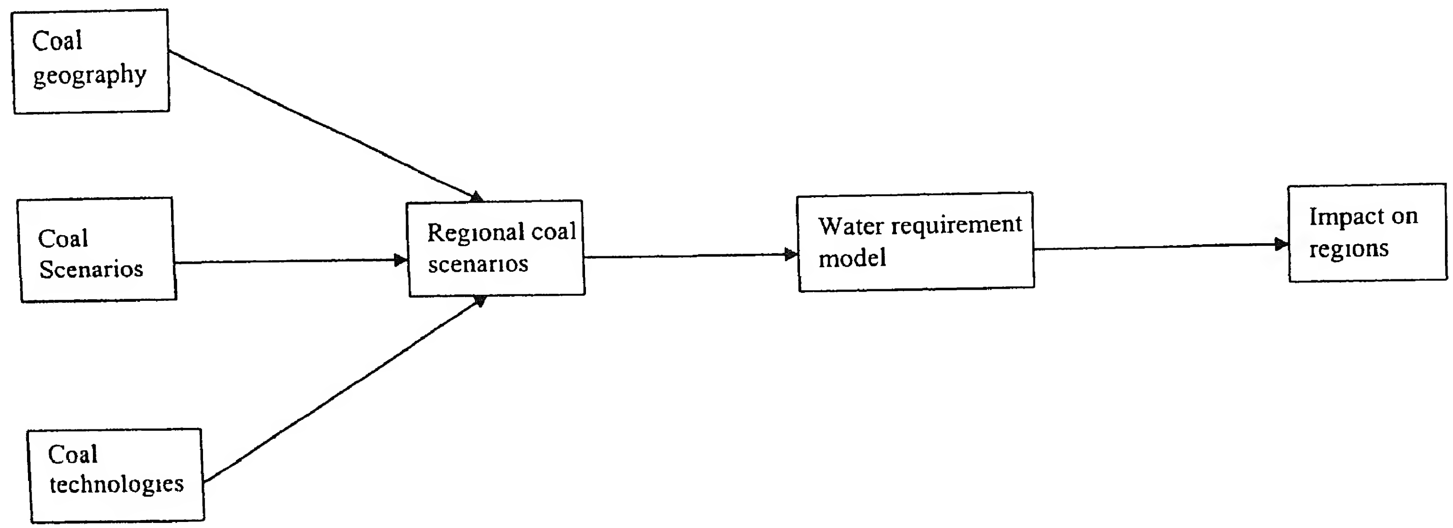
Water, energy, materials, manpower as well as land are the total resources consumed in making available fresh resources of fuel as in coal mining, coal conversion and further use To assess the range of natural (and other) resources required to achieve access to a desired quantity of an energy resource like coal, it is necessary to evaluate the factors outlined in Table 1

Table 1. Characteristics for resource and environment evaluation

Resource characteristics	Environment characteristics
Location & extent of deposit	Geology, stratigraphy
Deposit parameters: Type, geology, quality, etc	Land: topography soil, existing use, planned future use
Exploitation type of mining, equipment	Water storage, geology quantity, quality, current use, future demand

In 1984, Alcamo had attempted a comparative evaluation of the quantity of water required to expand coal production five fold in North America (USA & Canada) The water requirements of future coal development will depend on the kind of technology that would be used in the future and it was not obvious what their technologies would be. He adopted the following methodology Having decided on the coal scenario, (Figure 1) the model was used to evaluate the water needed for such a development and was compared with an intimate of [illegible]e.

Figure 1: Analytical approach to determining the impact of coal development on water resources



He arrived at the conclusion that four fold expansion of coal production would be constrained by the lack of readily available waters. Figure 2 shows that in order to meet a "demand" a path or "chain" through each of the six major coal sectors (1) mining (2) local transport. (3) processing; (4) regional transport; (5) conversion; (6) demand—must be followed. As Figure 2 notes, there are several possible technologies for each of these sectors.

Two types of mining are distinguished: surface and underground. Underground mining, is, in turn, subdivided into two categories, long-wall and room and pillar. The latter is by far the most common type o underground mining in India where long-wall is the predominant method used in Europe and the USSR. Hydraulic mining is being discussed as an alternative to long-wall mining but its future share of total underground mining is still unclear.

"Local transport" refers to the movement of coal between mining and processing centres, which are often in close proximity. Two forms of local transport are included - truck and conveyor.

Three alternatives are specified for coal processing: (enrichment facilities for low-grade coals destined for power plants; (b) cleaning and sizing facilities for higher-grade coals used in power plants or for residential or commercial heating; and © coke preparation for coking and other industrial coals.

"Regional transport" represents the distribution of coal from processing centres to either conversion facilities or demand centres. Five different transport modes are selected: barge, slurry pipeline, mixed train, unit train and trucks. A "mixed train" was used to refer to a train that carries non-coal cargo in addition to coal. A "unit train" carries only coal. Both types are currently used for short-distance haulage to conversion facilities or to other transportation modes.

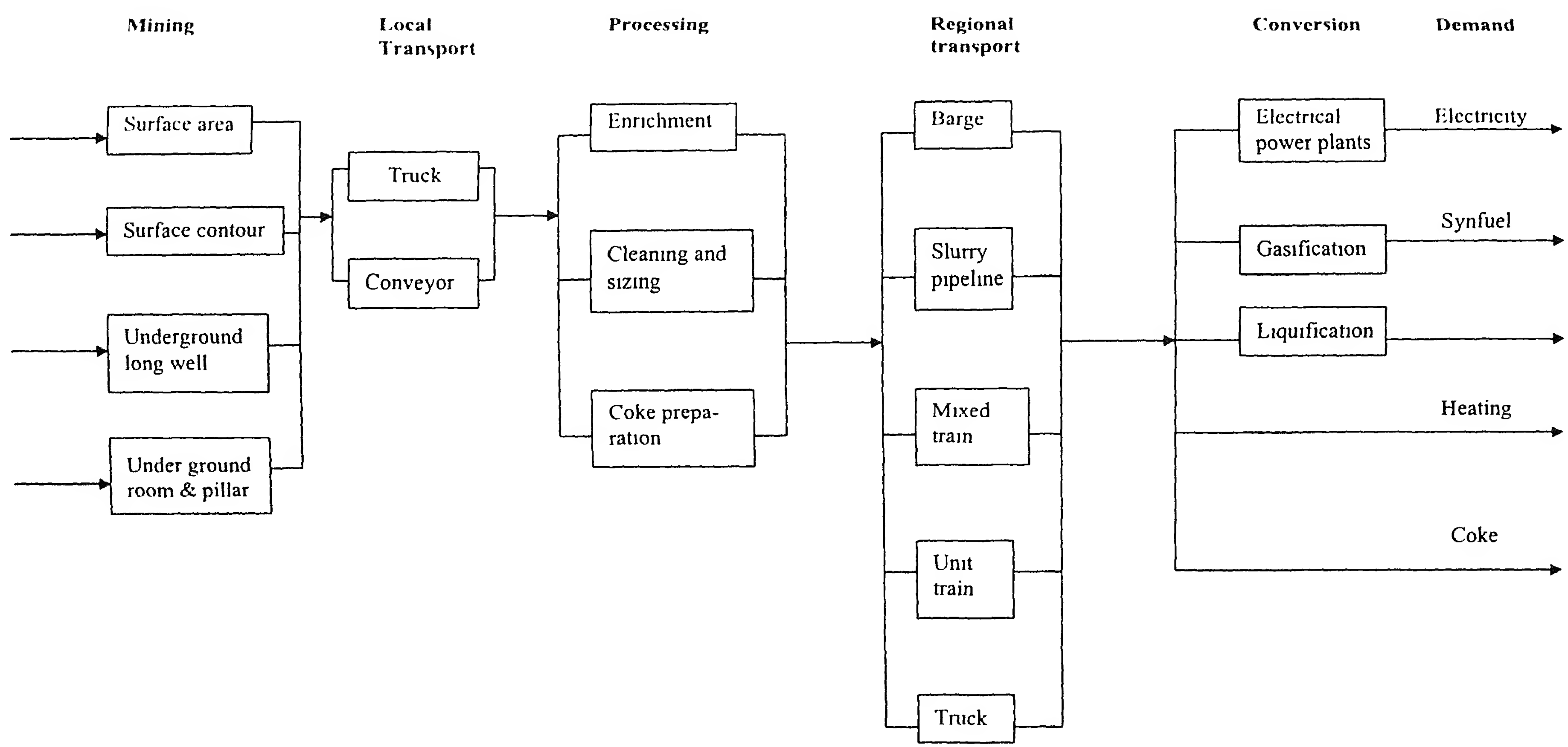
Figure 2 specifies two possibilities for coal conversion—electrical power plants and liquefaction. Power plants are assumed to be of the conventional combustion type Liquefaction plants are assumed to use the synthoil process. Synthoil consumes about the same amount of water as other feasible hydrogenation processes.

The last sector, demand, specifies four possible forms of energy form coal—electricity, synfuel, heating (which includes electrical production via cogeneration) and coke (which includes all industrial uses of coal, including feedstocks). The purpose of coal conversion is the production of alternative fuels (including motor fuels) or the generation of a range of chemical from coal by process routes such as gasification, direct and indirect liquefaction, hydro pyrolysis and plasma pyrolysis. The application of these techniques is essential if the large reserves of coal are to be substituted for less plentiful fuels. The process by which such conversion can be brought about are gasification and direct and indirect liquefaction. Definitions of these process are given in Table 2.

Table 2. Definition of various processes used in coal gassification & liquifaction

Gasification	Complete conversion of the organic matter of coal into gases (used for reduction, chemical synthesis and combustion)
Liquefaction	Conversion of as much as possible of the organic matter of coal into liquid products (used as fuels, gasoline, chemicals)
Process route 1	Direct liquefaction - Hydrogenation of coal at high pressure
Process route 2	Indirect liquefaction - Gasification of coal and consecutive catalytic conversion of the synthesis gas

Figure 2: Selection of technologies for the coal industry in the future



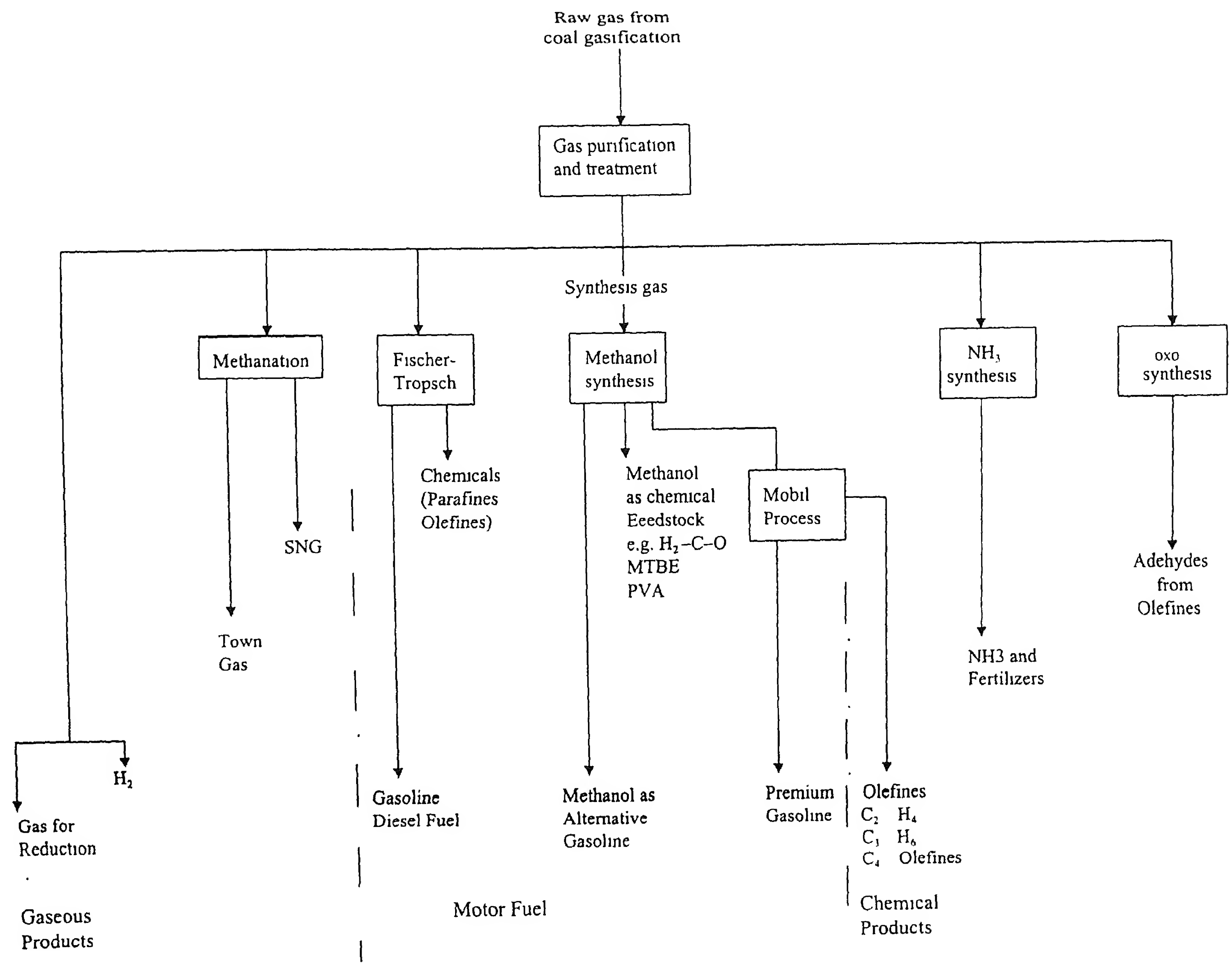
The essential feature of coal conversion by gasification and direct or indirect liquefaction is the conversion of coal into higher-grade products (Figure 3) such as fuel gases, motor fuels and chemicals which, at present, are mainly produced from oil and natural gas. Coal gasification and liquefaction processes are complex and a large variety of products can be obtained. The main product routes for raw gases from coal gasification are shown in Figure 3. Simple purification and treatment of raw gas yield a hydrogen-enhanced reduction gas and a lean gas for combustion. By additional methanation, town gas and substitute natural (SNG) can be produced. Another industrial scale process is methanol synthesis. Methanol is used as a solvent, as motor fuel, and is an important feedstock for chemical industries (e.g. for the production of lead free anti-knock agents such as MTBE, acetic anhydride and polyvinyl acetate). A future possibility is the large-scale production of motor fuel and power generation. Further processing of methanol by the mobil process given knock-proof gasoline and, under different reaction conditions, chemical products such as olefines. These technologies are under development. Synthesis gas is also the basis for NH_3-synthesis and so-called oxo-synthesis in which aldehydes are produced from olefines.

2.9 Environmental impacts

The mining activities lead to various environmental problems related to air, water and land apart from affecting the human health. Mining activities in many cases affects the ground water availability in the surrounding region by lowering of the water table. During mining the various operations leads to the generation of finer dust particulates which deteriorate the ambient air quality in and around the mining areas. A large amount of overburden dumps generated during open cast mining not only occupies the large portion of land but also deteriorates the soil and ground water quality by surface run-off and water seepage and causes safety problems in the area. Proper land reclamation practices both in technical and biological need to be adopted during planning and execution of the mining for proper dump management to improve its productivity, ecological integrity and economic and aesthetic value.

2.10 Occupational and environmental health problems

Health risks from coal arise from all stages of the coal fuel-cycle: prospecting, mining, beneficiation, transport, storage and utilization (direct combustion or following conversion to liquid or gaseous fuel). Health risks are part of the general environmental impacts that occur to natural, semi-natural and man-managed environmental systems. These include long-term and far-reaching impacts such as the effect the global emissions of carbon dioxide from coal burning will have on ambient temperatures and hence climate; the impacts of a local and regional nature arising from sulphur and nitrogen oxides emissions. Both will affect natural ecosystems (oceans, lakes and terrestrial ecosystems) and semi-natural ones such as grassland and forests as well as man-managed agricultural, horticultural and silvicultural ones.


Raw gas from coal gasification
Gas purification and treatment
Synthesis gas
Methanation
Fischer-Tropsch
Methanol synthesis
NH_3 synthesis
oxo synthesis
Mobil Process
SNG
Town Gas
Chemicals (Parafines Olefines)
Methanol as chemical Eeedstock e.g. H_2–C–O MTBE PVA
Adehydes from Olefines
NH3 and Fertilizers
H_2
Gas for Reduction
Gasoline Diesel Fuel
Methanol as Alternative Gasoline
Premium Gasoline
Olefines C_2 H_4 C_3 H_6 C_4 Olefines
Gaseous Products
Motor Fuel
Chemical Products

Health effects due to the coal fuel-cycle are experienced by human populations either as part of the workforce (occupational health risks) or as the general public (public health risks). Whereas it is usually a relatively simple matter to determine the size of the working population that is at risk, rather to estimate with any accuracy the size of the exposed general population that runs the risk of some degree of hazardous exposure.

2.11 Global environmental aspects

The environmental problems associated with coal production are, for the most part, site specific and controllable with today's technology. A more serious concern and uncertainty exists over the air pollution emitted during coal combustion. The effects of coal-induced air pollution are more widespread than the localized coal mining disruptions. Furthermore, the air pollution control technologies utilized in one area can actually intensify the level of pollution in another. In order to minimize the effect of emissions on local areas, utilities have used tall stacks to disperse gases and particles. Due to prevailing wind patterns and atmospheric conditions, these pollutants can be transported and deposited on other areas, creating both national and international air pollution problems.

The emissions from coal combustion include sulfur, nitrogen, and particles of ash. Once released into the atmosphere, these emissions reach with other natural and manmade gases and particles, making it difficult to distinguish the effects of one type of gas or particle from another or to determine the ultimate source of the pollutants. Despite these uncertainties, emissions from coal combustion are believed to be major contributors to air pollution More than half of the world's manmade sulfur emissions are attributed to this cause. These sulfur emissions, as well as nitrogen and particulate emissions, are associated with human illness and death; the creation of acid rain; and damage to plants animals and fish.

Therefore, the issues of concern are: the emissions resulting from the burning of coal contribute significantly to global climate change; the imbalances in the supply of and demand for energy, not only in the urban areas, but increasingly in rural areas as well.

3.0 Industrial transformation in South Asia

At the global level, IHDP has identified industrial transformation as one of the six priority research topics. On the basis of discussions held at the international workshop on IHDP-IT, organized by the Institute of Environmental Studies (IVM) of the Vrije Universitiet, Amsterdam, which outlines the following major research areas.

- System-analytical perspectives such as the Environmental Kuznets Curve, international mass balance research, eco-restructuring and developed-developing country interactions
- Industrial ecology including industrial networks, eco-efficiency, life cycle analysis, greening the industry and organizational issues.
- Consumers, including consumer choice issues and the role of consumers in decision making.

As has been studied, the most important and abundant source of energy for industries and power generation in the Asia Pacific Region is coal, which will continue to be the main

energy source for most of the countries in the region. Therefore, any attempts for retarding environmental degradation will have a large bearing on the power and coal sectors. Iron and Steel apart from cement will be the major coal consuming sectors. Focus on the technological and environment aspects of these sectors should be included in the research areas from the Industrial Transformation point of view.

3.1 Potential areas for focusing research efforts on IT

The technological developments and the associated economic and environmental implications form the major guiding factors for dwelling on the future directions. The latest economic policies of the South Asian Region indicate that the thrust will be on further liberalization of industrial, trade, and financial policies to increase efficiency, productivity and expanding access to international markets.

In a study carried out by TERI titled Growth with Resource Enchancement of Environment and Nature - `GREEN India 2047' . The objective of the study was to identify negative impacts on the environment that has been has been steadily deteriorating. The impacts on air, water and land were studied. The bio-diversity aspects and the impacts of pollution in cities and the loss of natural wealth in the countryside were also included in the study. The study tried to examine questions like: (a) What is the extent of damage in physical terms? (b) What are its causes, both direct and indirect? © How much – how many billions – has the damage cost us? (d) Does the price of economic development have to be a deteriorating environment? (e)
What can be done to reverse the degradation? The first phase of the project sought to set forth the extent of degradation of India's natural resources during the first fifty years of its independence and to assess the damage in economic terms. The results were comprehensively documented by a team of TERI researchers in a 350-page volume, which was presented to the Prime Minister of India.

The study also indicates that the primary goal of the society like India will have to promote economic growth and development and will remain paramount for quite some time. The study indicated that growth which is pursued in the mould of past structures and activities would actually be inhibited in due course, because the natural resources which sustain and provide environmental services for various economic activities-largely unpriced in the market-would actually decline in quality and quantity, such that output itself would suffer.

3.2 Sustainability concerns

The objective of the next phase of the GREEN India 2047 project is to articulate policies, measures, and strategies by which a smooth but rapid departure is brought about from past trends and practices, so that the Indian economic system and its basic structure become truly sustainable It is first necessary to get an assessment of some growth projections for the future, which are attempted on the assumption of a business-as-usual scenario. The projections of population, GDP (gross domestic product), and sectoral growth rates that were arrived at, based on current trends of consumption and production, appear staggering.

For instance, based on current patterns of development, the total production of finished steel in 2047 would be approximately 260 million tonnes; of aluminum, 7.6 million

tonnes; of cement, 1303 million tonnes; and of nitrogenous fertilizers, 27.3 million tonnes. In some cases, the total growth in the next 50 years based on a business-as-usual scenario would be higher. For instance, the increase in production of steel would be more than tenfold; in the case of cement, almost fifteenfold; and in the case of cotton textiles, the increase would be more than eightfold. Agricultural production also is expected to increase on a large scale during this period but somewhat slower than the expected growth of the industry. Overall, during the period 1990-2047, the GDP is projected to grow at a cumulative average of 5.3% a year and agriculture at 2.2% a year. The share of agriculture in the GDP would therefore, come down from 31.3% to a little more than 5% by the year 2047 while the share of industry would go up during the same period from 28.7% to 40.3%. The services sector would also increase its share from 34.6% to 47.4%.

4.0 The Indian Power Sector

The 15th Electric Power Survey (EPS) Committee set up by GoI, has estimated peak demand for power and energy over the next 15 years as 176,647 MW and 1,058,440 million kWh in the year 2012. We estimate that in order to keep up with the projected growth, additional capacity of 145,000 MW will be required by 2012. At an average price of US$ 1 million per MW, this capacity expansion would require about US$ 145 billion in just 15 years, or US$ 9.66 billion every year. This is a monumental task for any developing country, specially for India, where power generation has mostly been responsibility of central and state governments.

4.1 India's energy resources

Coal, oil, gas and hydroelectric potential constitute the conventional sources for electricity generation in the country. Of these, coal is the primary fuel for power generation because of its large proven reserves in the country. Oil and natural gas reserves are limited and account for a smaller proportion for power generation. The major consumers of natural gas are fertilizer and petrochemical plants where it is used as feedstock. Presently, coal & lignite has 53.4 percent share of commercial energy in the country compared to 16.4 percent for indigenous petroleum, 17.7 percent for imported petroleum, 2.7 percent for hydro, 8.9 percent for natural gas and 0.9 percent for nuclear energy.

The coal reserves are concentrated in the northern and eastern region and in some parts of central India. Lignite, though in very small quantity is found in some pockets of southern and western India. Table 3 shows the proven fossil and other fuel reserves. The non-conventional energy potential in India is discussed under section 5.

Table 3 **India's commercial energy resources**

Coal	70 billion tons
Crude oil	727 million tons
Natural gas	623 billion cubic metres
Hydro (large)	84,000 MW
Uranium	6,700 tonnes
Thorium	363,000 tonnes

Sources Economic Survey 1996/97, Indian Petroleum and Natural Gas Statistics, Annual Report, MoC

4.2 Constraints in the development of power sector

The power sector in the states is the responsibility of the state electricity boards (SEB) who generate, distribute, set tariff and collect revenues. A review of the financial performance of the SEBs indicates that they are incurring very heavy losses as a result of unremunerative tariffs mainly in the agricultural and domestic sectors. Other reasons for their poor financial performance are high commercial losses, substantial arrears receivable and high distribution losses. With the reduction in the budgetary support from the GoI and the factors just mentioned it is unlikely that the SEBs will be in a position to make investment in new capacity additions. High capital cost associated with high-tech power generation technologies drives India to continue using available conventional technology.

4.2.1 *Infrastructure*

Although India has substantial coal but there has been little investment in the development of new mines. Besides, the production in the existing mines has been falling due to various reasons. The gap between supply and demand is widening and the thermal power plants may have to resort to import coal to fill the short fall. Transportation of coal supplies is also a major issue because load centres are widely distributed across the country. The Indian Railways play a crucial part in the transportation of coal to the various thermal power plants. The available infrastructure is highly congested. There are major constraints on long haul coal movement by rail routes to both the west and east coasts. In case of coastal movement, ports are also under strain, and report more than 100 percent capacity utilization. Though there are expansion plans lined up, development of new facilities will take time to fructify due to resource constraints. Even when facilities are available, reliability of service remains a problem Coastal movement has been increasing consistently over the years with increasing demand from coastal power stations. This affects the choice of fuel for power generation.

4.2.2 *Institutional constraints*

The IPPs are faced with considerable difficulties in obtaining the required clearances resulting in delay of capacity addition. However, the major constraint is the signing of the power purchase agreement (PPA) with the utilities. Besides the financial position of the SEBs being pathetic, IPPs find it very difficult to procure the needed finances for the project. It may affect the selection of advanced technologies because of the risks involved and high capital investment

4.3 Coal based power generating technologies

The coal is India's primary source of energy, accounting 53.4 percent of the country's total commercial energy consumption. India has an abundant supply of coal but the only drawback is its high ash contents resulting lower heating value. This also makes it less competitive with the imported coal that has much lower ash content. In India more power is produced by coal then any other fuel. This is likely to remain so for the future. The various coals based options considered are pulverized coal (sub-critical and sup-critical), atmospheric and pressurized fluidized bed combustion and integrated gasification combined cycle systems.

4.3.1 PC Boiler (Sub-critical and Sup-critical)

The pulverized coal fired plant represents the most commonly available technology. In PC combustion the coal is first ground in a mill to a fine powder, along with preheated combustion air. Some of the incombustible matter and unburned carbon is removed at the base of the furnace as bottom ash. The remainder of the ash is carried forward with the hot gases from the furnace. These gases are cooled before an electrostatic precipitator is used to remove residual fly ash. The flue gases are released in the atmosphere via stack. The heat recovered in the boiler and from the hot gases is used to raise HP steam that generates electricity via steam turbine. The efficiency ratings of a large utility size power plant are 37 % or higher, and that of a super-critical steam conditions, multiple reheat and other refinements can exceed 40 % efficiency.

In the case of coal having high sulfur content, FGD is added in order to meet environmental legislation (if it is enforced) relating to SOx emissions. Currently there are no SOx emission standards in India, however in highly industrialized areas use of FGD may be required. There are roughly 19 hot spots in India were stringent environmental emissions are set by the Central Pollution Control Board (CPCB) and State Pollution Control Boards (SPCB). There are various methods of post combustion sulfur removal but the wet limestone/gypsum scrubbing is the most common FGD method in use throughout the world. These processes are used for boiler applications with high to low sulfur fuels. In this process SO_2 containing flue gases reacts with a slurry of limestone in a spray of air and water to produce a hydrated calcium sulfate, gypsum that can be a valuable by-product. The sub-critical boiler operates at temperature and pressure range of about 540°C and 165 bar respectively. While the super-critical boilers generally operates in the temperature and pressure range of 560 - 580°C and 250 to 265 bar respectively. The operating parameters have the impacts on the efficiency of the power cycle.

Technological features

- Is suitable for almost any coal mined throughout the world
- It is economically suitable for a very wide range of boiler capacities
- Provides wide flexibility in operation and high thermal efficiency
- Must have proper coal preparation and handling equipment including the moisture removal
- Must have proper means of handling the ash refuse, and must have control for atmospheric emissions arising from elements in the coal and from the combustion process
- Slow O&M cost as compared to other clean coal technologies

Commercial availability
It is a well proven and easily available technology with substantial manufacturing capability world over. PC technology is available in sizes up to 1000 MW. This technology has also been mastered for inferior quality of Indian coal by BHEL. For Indian coal having high ash content the overall size of boiler is large when compared to imported coals where the higher calorific value and low ash content reduces the size of boiler and hence the cost of electricity. The super-critical boilers are not available in India.

4.3.2 Atmospheric fluidized-bed combustion
AFBC technologies are adaptable to both new and existing installations, work well in combination with other technologies, and are suitable for many local coals. In AFBC, the coal together with some limestone is crushed and then fed to the top of the fluidized bed. This bed contains a mixture of unburned coal, ash and an inert bed material, which is fluidized by injection of air. The temperature in the boiler typically ranges from 820°C to 840°C. This low temperature is the chief advantages of AFBC because in this temperature range thermal NO_X is much less likely to form. Furthermore, limestone injected into the furnace captures the sulfur and removes it as a dry by-product. This can greatly remove the SO_X emissions from the plant. During combustion heat is transferred to a steam cycle via heat exchanger tubes in the fluidized bed itself. This steam is used for power generation in a conventional cycle, just as in the case of pulverized coal system. Two basic designs variations are possible, bubbling and circulating AFBC.

Apart from reducing the emissions, the lower combustion temperatures permit burning high fouling and slagging fuels at temperature below their ash fusion temperature. As a result many of the boiler operating problems associated with Indian coals are greatly reduced For Indian coal which contain high ash, the AFBC boiler offer an advantage in fuel preparation over pulverized coal systems. The Indian coal requires greater installed pulverizer capacity and requires frequent maintenance. Where as for AFBC boilers the crushed fuel size is 6 5 mm as against -200 mm mesh for pulverized coal boiler. It also offers advantage of fuel flexibility in terms of quality of coal used.

Technological features

- AFBC can remove up to 70-95% SO_2
- Bubbling type AFBC removes SO_2 in the range of 70-90 % while circulating type up to 95 %
- NO_X emissions in the range of 100-300 PPM
- Boiler and overall plant efficiency are similar to those of PC
- AFBC technology is suitable for new plants and retrofit applications
- Suitable for high sulfur coals

Commercial availability
This technology was first introduced in the 1960s. Since then the development is concentrated only in the small-scale boilers. AFBC technology is commercially available for up to 200 MW A number of projects are also planned in the 250 to 350 MW size range. AFBC boiler of 125 MW in Finland and 150 MW of size in Mexico is operating. Another plant of 250 MW is in operation since 1995 in France.

In India, BHEL has been carrying out R&D work on fluidized bed since 1975 and has developed circulating type boilers up to capacity rating of 125 MW (390 tph steam flow) for high ash coal and lignite fired.

4.3.3 Pressurized fluidized-bed combustion

This technology uses a combustion process similar to that of AFBC, but the boiler operates at an elevated pressure of 5 to 20 bar. Heat is removed from the fluidized bed to a steam cycle, as with AFBC. The hot gases resulting from the combustion are at high pressure and, when they have been cleaned using either cyclones or filters, they are suitable for feeding to a gas turbine, which can convert efficiently the energy in the hot pressurized gas to electricity. Heat is also recovered from the gas turbine exhaust to the steam cycle. In this technology limestone is used in the bed to limit the sulfur emissions . This particular technology is also suitable for the Indian coal and has all the advantages mentioned in the AFBC technology.

Technological features

PFBC technology has the advantages of AFBC technology (high SO_2 removal, low-NO_X emissions, ability to burn low-quality fuels, and fuel flexibility) and in addition the potential for achieving the higher plant efficiency (up to 45 %) than PC or AFBC (36.5 %). It also offers lower capital cost than IGCC or pulverized-coal with FGD.

- More than 90 % SO_2 removal
- NO_X emissions at 100 to 200 PPM
- Up to 43 percent efficiency in a combined cycle arrangement

Commercial availability

At present four PFBC plants are in operation

- The Varian plant (135 MW & 220 MW of district heating), Stockholm. This plant is now in full commercial operation having met all availability and performance target set for the first three years of operation and is owned by Stockholm Energy.
- The Escatron plant owned by utility Empresa Nacional de Electricidad SA (ENDESA), Spain
- The Tidd plant, Ohio, USA owned by American Electric Power (AEP)
- The Wakamatsu plant owned by Electric Power Development Company of Japan
- Another PFBC plant at Karita of about 360 MW capacity in Japan is likely to be commissioned in 1998/99.

4.3.4 Integrated gasification/combined cycle power plants

Gasification is a well proven technology to convert a variety of hydrocarbon feed stocks like coal, lignite, oil distillates, residues, and natural gas into synthesis gas ("syngas"). Gasification is the partial combustion of hydrocarbon feed with air or oxygen in feed ratio's preventing complete combustion but producing synthesis gas. The syngas is essentially a mixture of carbon monoxide and hydrogen. Gasifier temperatures are ranging between 800 and 1500 ^{0}C. The raw syngas produced is cooled before entering gas clean up, such as cyclones and ceramic filter to remove contaminants followed by gas treatment to reduce SO_X and NO_X to very low levels. This cleaned gas is burned inside the gas turbine combustion chamber, leading to higher efficiency cycles. There are several different designs of gasifier available, but these basically fall into one of the three categories: fluidized bed, entrained

flow and fixed or moving bed gasifiers. The choice of gasification technology will be determined by technological factors in relation to intended feed and desired products and factors like costs, experience and track record. Gasification for power generation has been stimulated by the energy crisis in the seventies and this interest is further enhanced by the recognition that gasification is able to meet stringent environmental specifications converting low value "dirty" feed stocks to electricity with a high efficiency .

The primary constraint to the application of gasification and IGCC plants in India is that the technology needs further demonstration, the costs are higher than those of conventional technologies, and the fact that environmental regulations do not require the high SO_2 removal and low NO_X emissions as achieved by IGCC.

Status in India

BHEL has designed and set up a 18 tpd pilot scale pressurized process equipment development at Hyderabad. This facility has been used for designing 150 tpd pressurized fluidized-bed gasifier for setting up a 6 MW of electrical output pilot test facility. This is an entrained-bed gasifier using 46 % ash coal operating around a temperature of 1500 ^{0}C. This facility has been in operation since 1990.

A 57 2 MW IGCC plant using lignite as a feedstock is likely to be operational by November 1997 in Kutch region of Gujarat state. This features the U-Gas gasification technology, developed by Institute of Gas Technology, Chicago, USA. It is based on air blown gasifier with hot gas clean-up system. Hindustan Petroleum Corporation Ltd. (HPCL) is planning to set up a 260 MW IGCC plant at Bhatinda in the North Indian state of Punjab based on Petrocoke. The petrocoke will be a by product from their new refinery at the same site. India's growing demand for high speed diesel or gas oil (with low Sulfur distillates) has led HPCL to adopt a Delayed Coker technology yielding in Petrocoke. Although they have not decided on the technology but have plans to gasify high sulfur content petrocoke to produce syngas and subsequently remove sulfur as H_2S.

Technological features

This technology is in the demonstration phase and is more expensive than other alternatives. IGCC plants can achieve more than 50 percent of efficiency with advanced gas turbines, greater than 99 percent SO_2 removal, and NO_X below 50 PPM. Entrained IGCC technologies are suitable for low ash coals. High ash coals, such as that of India, will require fluidized-bed gasification process. Time for construction is expected to be similar to pulverized coal plant with FGD unit. However, phased construction can improve the economics of the IGCC plant by producing power when the gas turbine is installed.

Commercial availability

A 100 MW IGCC plant at the Cool Water site in America is in operation for the past five years, during which time its performance with a wide variety of feed stock was validated. Since then a number of design and demonstration projects have come up in US and Europe. Some of these projects are:

- A 265 MW plant at Wabash River using the Destec Two Stage Oxygen Blown entrained flow gasifier with Cold Gas Clean-up.
- A 95 MW plant at Pinon Pine using a KRW Fluidized Bed Air Blown Gasifier with Hot Gas Clean-up.

- A 55 MW plant at Tom's Creek utilizing a Tampella U-Gas Fluidized Bed Air blown gasifier with fluid bed hot gas clean-up.
- A 250 MW plant using the Texaco, Oxygen Blown Gasifier with Entrained, Air Blown Gasifier with Hot and Cold Gas Clean -up at Tampa Electric.
- 253 MW Demkolec Plant: Potential to be scaled up to 550 MW plant with 51 % net efficiency, and installed cost of around $1500/kW.
- 335 MW Puertollano Plant using PRENFLO gasifier in Spain.
- 35 MW EL Dorado Plant
- 42 MW Sterling Plant
- 500 MW ISAB Italian refinery project is scheduled to be operational by November 1999.

4.4 Pollutants from advanced power generating technologies

The efficiency of coal conversion in (say Indian) power stations is low; the average gross conversion efficiency is about 28%. The present design gross efficiency is about 35%, and enhancing power station performance to increase the operating efficiency to the design efficiency would increase aggregate power output (at the same input rate) by nearly 15% Pulverized coal electric power generation is the technological choice in the utilities. The principal cause for low efficiency is poor and varying quantities of coal, poor maintenance and operating practices.

There are many technologies that have the potential to replace pulverized coal combustion as the primary coal-to-electricity technology. FBC (fluidised bed combustion) is already commercially available at capacities up to about 200 MW. In addition, there are advanced technologies that show promise. IGCC (integrated gasifier combined cycle) technology is being tested for techno-economic viability; PFBCC (pressurized fluidised bed combined cycle) is undergoing technological development; and IG-MCFC (integrated gasifier molten carbonate fuel cell) technology is still at the pre-pilot plant stage. The expected efficiencies of these technologies and the estimated emission levels for suspended particulate matter (SPM), sulphur dioxide (SO_2), oxides on nitrogen (NO_x) and carbondioxide (CO_2) are given in Table 4.

Table 4: Pollution loads of advanced power generating technologies

Technology	Expected* efficiency (%)	Estimated emissions (g/Kwh)			
PFBCC	38-42	126	0.029	1.42	911
IGCC	40-48	9.5	4.000	0.43	921
IG-MCFC	40-46	6.2	0.096	0 29	778
PC boiler/steam turbine	35-40	205	3 000	9.60	930

The efficiencies have been updated based on the latest technological developments

Source Dr Ajay Mathur, 1994, Potential for introducing advanced technologies for power generation in India, in Proceedings of the Training Workshop on "Environmental Issues Related to Electric Power Generation Projects in India," 4-6 March 1993, Jaipur, India, Manila Asian Development Bank. 167-184pp.

Clean coal technologies add about $0.01 per kilowatt hour to the cost of electricity. Higher-efficiency clean coal technologies add between 15 and 30 percent to the capital cost of power plants in Asia. Therefore, a key factor in projecting emission levels during the next 30 years is the prospect for low-income Asian countries to develop and adopt lower cost, clean technologies.

The extent to which renewable energy sources will become competitive with fossil fuels is an important aspect to be studied. The cost of renewable energy, especially solar energy, with which Asia is richly endowed, has been declining at the rate of 3 to 5 percent a year. If this rate continues, solar energy would become competitive with fossil fuels for some applications between 2010 and 2020, provided that governments remove their subsidies on fossil fuels. Small-scale solar energy production is already competitive for rural electrification in remote areas. Biomass, wind, and geothermal energy provision will be competitive with conventional power technologies.

4.5 Environmental impacts due to combustion of coal

The environmental impacts of increased coal utilization are primarily the result of the emission of air pollutants arising from combustion processes, or coal gasification or liquefaction plants. These pollutants may be distributed over a relatively large area, whose extent depends upon the design and mode of operation of the combustion or conversion process. Liquid and solid wastes arising from coal utilization generally represent more localized problems. These are discussed along with the effects and coal mining, treatment or transport in other chapters.

The pollutants traditionally associated with coal combustion are sulphur dioxide (SO_2) and smoke (particulates). Modern coal combustion systems are designed to avoid the continuous discharge of particulates or else, in the case of large plants, to eliminate them from flue gases almost entirely by electrostatic precipitation, cyclonic devices or bag filters. In consequence, increased coal utilization should not result in serious smoke pollution problems However, the control of SO_2 emissions has proved less feasible in technological or economic terms, and thus SO_2 must be considered a potential environmental hazard, particularly in view of the concerns arising from transboundary dispersion. Recently attention has become focused on nitrogen oxides (NO_x) emitted from coal-fired pore stations is in the form of nitric oxide, which becomes oxidized rapidly in the air to nitrogen dioxide (NO_2) (CENE, 1981). Small amounts of nitrous oxide (N_2O) arise from combustion processes, although most atmospheric N_2O is of natural biological origin. N_2O emissions constitute a potential global problem in view of their possible role in stratospheric ozone (O_3) depletion and in their contribution to the "greenhouse effect". With distance from the source, both SO_2 and NO_2 become increasingly oxidized in the atmosphere. Both dry and wet deposition occur eventually on the earth's surface. Wet deposition, mainly in aerosol form, occurs by in-cloud (rainout) and below-cloud (washout) scavenging. Other emissions of significance from coal utilization include carbon dioxide (CO_2), trace metals (including radionuclides).

4.6 Fly ash

A major source of solid waste would be from the increasing consumption of coal in the country. It is estimated that on a business-as-usual basis, the total annual consumption of coal would have reached 1384 million tonnes by 2047. With an average ash content of 30% (on the assumption of 100% coal washing at the mines), the total ash generated in 2047 would be 449.8 million tonnes. Of this, 90.0 million tonnes would be bottom ash and 359.8 million tonnes would be fly ash. Currently in most of the thermal power plants in the country, ash is collected in wet form, which makes it difficult to utilize it for most applications. By 2020, it is assumed that new power plants would have dry fly ash collection facilities. Hence, it would be possible to utilize 100% of the ash. The bottom ash, however, would be in slurry form and would have to be dumped in ash ponds for disposal. By 2047,8000 hectares of land would be required for disposal of this bottom ash. The enormous resources that would go into coal transportation in the future would be unsustainable, given the geographical confines of our coal deposits and the high ash content.

Coal gasification would be a technology that provides and answer. Even after 40 years of R&D on coal gasification, India has still not produced in a viable technology. The region needs a major breakthrough in this area in the next decade. Another important implication of these estimates is the need for a clear technology development policy. If by 2020 India need to utilize fly ash collected in dry form, we must have in place the technologies that are commercially viable and functionally acceptable to make this possible. This really means that the R&D policies must clearly target fly ash utilization in an acceptable manner as a clear-cut and time-bound goal to be reached within the next 10 years or so. This will not only be creating a serious environmental problem by not pursuing this area of priority, but are also losing a valuable resource that could provide substantial quantities of building material in a range of applications. As was mentioned earlier, the cement production estimated on a business-as-usual basis in 2047 would be 1303 million tonnes. If fly ash could be used as a building material, then to that extent the demand for cement would go down. Improved building techniques and development of superior grades of cement could bring about a further reduction in demand. Consequently, it is possible to foresee that the total demand for cement in 2047 could be limited to almost half of the quantity projected under business-as-usual scenario through plans and policy initiatives that could be taken in hand almost immediately. This would also halve the environmental impacts of cement production, which are generally severe, and the effects of the whole cement cycle including lime quarrying, etc.

Predicting technological progress is almost impossible. Nevertheless, new or emerging technologies are likely to affect the environment in the long run: cleaner and more efficient energy production, pollution abatement, and resource conservation technologies that will lower the costs of controlling pollution, treating waste, and conserving natural resources.

5.0 Renewable energy technologies (RETs)

Renewable energy can play a significant role is de-carbonizing power generation and for meeting the industrial and residential heat. Quite a few technologies are commercially available and are being used in India and other parts of Asia in large numbers such as wind, solar thermal, solar PV, biomass, biogas etc. However, there is still a very large scope for

promoting them. It is expected that at least 40 percent of the grid based power generation will be available from RETs by the year 2050.

The most important opportunity in the spread of RETs lies in creating confidence and conditions whereby private initiatives would come into existence at a decentralized level. A major barrier in this regard is the attitude of electric utilities, which still pursue the conventional approach of favouring large-scale centralized application of power generation and distribution, and do not provide a level playing field to non-conventional and decentralized options. There is, of course, a slow acceptance by them of grid-based decentralized power generation, such as, through wind farms and cogeneration. However, there is still a dominant resistance to promoting decentralized distribution systems that may function autonomously. The result is that there is an acceleration of technological improvement in grid-based power generation technologies, such as, wind machines for producing electricity, but hardly any serious effort in developing wind-pumping systems, or biomass gasifiers that could function on a stand-alone basis and benefit large areas where ground water pumping is a major activity.

While it would not be proper to over-simplify the complexities that characterize the rural energy scene in most developing countries, it has become increasingly clear that small incremental steps will not lead to optimality in the utilization of renewable energy resources. Hence, a major push is needed by which the institutional barriers inhibiting the movement towards optimality can be tackled. A complete overhaul of legislative and institutional arrangements by which energy supply organizations carry on their business today has to start immediately. A serious debate and resolution of the problems in this regard is long overdue, and no further time should be wasted. Table 5 below gives the potential for renewable energy technologies in India as per the Ministry of Non-conventional Energy Sources.

Table 5 Estimated potential for renewable energy technologies in India

Sources/systems	Potential
Biogas plants (No.)	12 million
Biomass	17,000 MW
Solar energy	20 MW/sq. Km
Wind energy	20,000 MW
Small hydro power	10,000 MW
Ocean energy	50,000 MW

5.1 Hydro power

The Government of India has estimated that small hydro has a potential of 10 GW, although only 220 MW has currently been exploited (predominantly in isolated mountainous regions). Long construction lead-times, potential environmental opposition to larger schemes, and relatively high capital costs do not facilitate the penetration of large hydro power schemes, despite promising potential in many areas. The total gross hydro capacity from small and large facilities combined is about 85 GW. Micro hydro plants (up to 3 MW) appear to have a more promising future, with almost 236 MW under construction. However, hydro's share of total generation has been declining because of the rapid pace of capacity additions and government policies to utilize low-cost coal.

The small hydro programme in India is implemented by at least three government agencies. The mechanisms include subsidies, soft loans, and grants. A main source of current funding is a US$70 million World Bank loan for setting up projects of 15 MW capacity.

5.2 Wind

The Indian Ministry of Non-conventional Energy Sources has stated that the country can become the world's second leading producer of wind energy (after the US) during the next three years. The current installed capacity of wind power generation is around 1000 MW and is the fourth largest in the world.

5.3 Solar Power

The Department of Science and Technology initiated a solar PV programme in 1975, the Central Electronics Limited, a public sector electronics company, headed a programme of product development while materials and basic research were undertaken by academic institutions and R&D laboratories. The total installed manufacturing capacity of 100 kW, was commissioned in 1994.

Unfortunately, the reliability of PV systems has been poor due to the poor design of associated systems components, vandalism, and neglect. Under laboratory conditions, with trained technicians providing regular maintenance, the systems should be nearly cost-competitive with grid supplies. In the US, the Enron Corporation reported that it would build a US $150 million, 100 MW solar plant, 10 times larger than any other existing PV plant expected to be on-line by the end of 1996. Enron believes that it can deliver solar electricity at US$0.055/kWh. Ambones Corporation, also in the US, claims to have achieved 20% conversion efficiency for high concentration PV arrays which will lead to capital costs of $1.50/W of installed capacity or $0.06/kWh for generating electricity (Modern Power Systems, 1994). Both examples indicate declining cost potential for PV cells and increasing potential for rural India where diesel generators are the principal means of electrification.

5.4 Biomass combustion and gasification

Several options are available to further exploit biomass potential in rural India. For example, the combustion of crop residues, such as, bagasse could be used to produce electricity and heat. Several projects are in the planning stages or under construction for plants in the 150 MW range.. Biomass-fired generating plants are proven technologies with substantial operating histories (30 years or more in North America for similar sized plants) to justify additional capacity expansion. However, due to limited availability or cultivation of feedstock, near-term potential is limited, except where large quantities of bagasse, wood chips, or other fuels are readily available. About 64 mt of bagasse and an equivalent amount of wheat straw are available annually, although the collection and transportation costs for such low density fuels have not been calculated. Bagasse is already available in relatively large quantities in sugar mills, where it is transported to extract sugar.

There are plans to includes a demonstration programme for the use of fast-growing woody species which could be used as a renewable feedstock. Energy plantations are also being considered for reclamation of saline, alkaline, and waterlogged soils, and in otherwise difficult to cultivate areas, such as, steep and hilly ravines. The principal objective of India's programme for energy plantations is to improve rural employment. As of now, about 1800 hectares have been brought under cultivation specifically for this purpose. In addition, some combination of woody crops and grasses grown in rotation or in combination with food crops could provide additional biomass for conversion into electricity and gaseous liquid fuels. A grid-connected pilot biomass gasification plant (500 kW) is being set up in Gujarat.

Biomass gasification is a technology promoted since 1986 to offset diesel use for irrigation a substitute for electrical pumping of groundwater. Biomass gasification can also produce fuel for diesel-fired generation equipment. Advanced technologies like BIG/STIG should significantly improve the power output with same quantum of biomass.

The distorted price of the diesel pumpsets made it impossible to determine the level of user acceptance of the gasifier technology; in many cases the gasifier was decoupled from the diesel engine.

6.0 Technologies for steel sector

Steel sector is the second largest after the power sector in consumption of coal, only 15% of the Indian coal reserves are coking variety suitable for use in steel making, the consumption and demand of coking coal for steel sector is as follows:

	1994	**2001-02**	**2006-07**
Coking coal, MT	33	50	60
%	(13%)	(12%)	(11%)

Even the meager deposits of coking coal predominantly contain high ash and are difficult to clean. There is wide fluctuation of ash content in the coals supplied to steel plants. The high ash and variation affects the performance and smooth operation of the blast furnace. The ash content in blend for feeding to blast furnace varies from 20 to 22% whereas the steel plants are designed for the consistent quality of mined coal is getting deteriorated. Every 1% increase in the ash content result in the increase of coke rate in blast furnace by 23-25 Kg thm[6] Thus ash content in coal is very critical for steel sector.

The imports of prime coking coals are steadily increasing on the ground that the domestic coking coals are deficient in quality and quantity. Therefore technologies are required to utilize indigenously available coking coals and also non coking coals for steel making to reduce the dependence on imports.

Partial Briquetting of coal charge (PBCC) enables to use higher proportion of semi coking coal in the coal blend without affecting the coke strength. SAIL is adopting PBCC

technology. Stamp charging helps in obtaining better coke strength using inferior coal charge. TISCO has adopted this technology utilizing 60-70% of medium coking coal. Selective crushing is another technology in which coal is homogeneously crushed.

6.1 Solvent refined coal

This is a coking agent prepared from non-coking coals/washery middlings as feedstock. Addition of about 8-10% solvent refined coal in the coking blend has shown significant improvements in coke strength by way of decrease in M10 value apart form reduction in ash content of the coke by 1-2%. The technology is developed up to pilot scale of 0.5 tpd by CFRI, India. This coal can replace imported coal but it is yet to be demonstrated with Indian coals.

6.2 Formed coke

A number of processes have been developed abroad for the production of formed coke on commercial scale in Germany, Poland, Japan and France etc. based on non-coking coal and briquetting the char with binder prepared by processing the tar and thereafter curing it. The formed coke produced has been successfully tested in low shaft furnace. The adoption of formed coke in metallurgical application can lead to conservation of coking coals.

6.3 Coke dry cooling and non-recovery coke oven

In coke making wet quenching of hot coke causes atmospheric pollution by emitting about 500 grams of dust (40% of total dust emission in coke ovens) and 156 grams of chemical pollutants per tonne of coke. Coke dry cooling eliminates this pollution, recovers energy form hot coke and improves coke quality. This results in the reduction of coke rate in the blast furnace up to 3%.

In comparison to by-product recovery ovens, the modern non-recovery type have several advantages such as pollution free, flexible, profitable and no handling of byproducts. Two large scale non-recovery coke oven plants of capacity 0.7 mtpa and 0.24 mtpa are operating in USA and Australia. In India a oven called Kumbhraj is developed by CFRI.

6.4 Coke rate reduction in blast furnace

Metallurgical coal is scarce in India and consumption of coke made form it constitutes the most significant cost factor in the production of hot metal. Energy accounts for nearly 35% of total cost of steel production and coking coal provides around 80% of energy input. Therefore effort are continuously being made to reduce the coke consumption in blast furnace. The coke rate in the blast furnaces in UK, Germany and Japan range from 450-525 Kg/thm as against 675-750 Kg. thm in India. The advanced technologies, relevant to coke/coal in the reduction of coke rate are:

- Upgradation of coke quality.
- Injection of coal dust or coal gas production from non coking coal into the blast furnace, resulting in the reduction of coke requirement up to 40%. The rate of coal dust injection practised in the advanced countries is in the range of 80-90 Kg/thm as against 50-70 practised in India.

This is a suitable technology for India The rate of coal dust injection can be increased. The ash content in coal need to be below 15% which is a constraint for India in popularizing this technology.

6.5 Alternative iron making processes

Blast furnace iron making, the most widespread iron making technology is capital intensive and dependent on metallurgical coal. These limitations have led to renewed interests in the following alternative iron making processes which are based on non-coking coal.

- Direct reduction
- Smelting reduction

Direct reduction includes a large number of processes in which iron ore or pellets are reduced in the solid state by either solid or gaseous reducing agents. In these processes reformed natural gas or non coking coal is mainly used as the reductant and primarily source of energy. The final product after reduction is solid which must be melted during steel making like scrap, mostly in electric arc furnace. The processes used for gas based reduction are retort, shaft furnaces and fluid beds and for coal based are rotary kilns. Gas based processes account for 90% of World's installed capacity because of certain advantages of gas based over coal based.

Smelting reduction as the name suggests involves both reduction and smelting like in a blast furnace where both steps occur in a single reactor. A number of salting reduction processes have been developed which can be classified into 3 categories: shaft furnace processes, electrical processes and converter processes. Out of all the smelting reduction processes, COREX is the only one which has reached the commercial stage. A commercial plant of 300.000 tpa was started in 1989 in South Africa. A second commercial plant 600, 000 tpa is scheduled to start soon in South Korea. The capital cost of a typical 300,000 tpa COREX plant is estimated as US$ 250 million. A plant of 1.25 million tpa is under construction in India. The main advantages of COREX process are:

- Lower emissions than blast furnace route
- Wide range of non coking coals can be used
- Lower investments and production costs.

The smelting reduction technology has a lot of potential for the production of ferroalloys. Japanese are working on a process similar to COREX for the manufacture of

ferrochrome. This process is less energy intensive compared to the submerged arc process normally employed for making ferrochrome and other ferroalloys.

ROMELT or Ferrous Liquid Phase Recovery Process is another smelting reduction technology developed using non coking coal. This is developed by Moscow Institute of Steel & Alloys, CIS. A semi commercial plant of about 300,000-350,000 tonnes of liquid iron per annum has been set up there. This process is considered unique for the following reasons.

- The process can use iron ore in the size range up to 20 mm including fines without any pretreatment of beneficiation and agglomeration.
- The process can use run of mine non-coking coal in the size range up to 20 mm
- Design and operation of the process are simple
- Cost of production of hot metal is projected to be 10 to 30% lower compared to blast furnace.

The drawbacks and technical issues yet to be addressed are,

- The Russian plant used non coking coals of low ash and low volatile matter. Performance with high ash and high VM coals such as those available in India have not been demonstrated.
- The process is oxygen intensive around 700 NM^3/Thm
- The waste gases from the furnace carry away 25-30% of the energy input upsetting the economics of the process

6.6 Mini blast furnace

The large blast furnaces are associated with high investment, large capacity for economy of production, stringent quality of raw materials etc. While the mini blast furnace is characterized with lower investments, smaller capacities, lower gestation periods and market oriented locations.

A large number of mini blast furnaces are operating in Brazil, China and India. Operation of the mini blast furnaces with charcoal and coke has been extensively tested. China uses metallurgical coke and the coke rate varies between 550 to 630 Kg/thm. Injection of pulverized anthracite coal to the extent of 60 Kg/thm has been tried which has brought down the coke rate by about 40-50 Kg/thm. A mini blast furnace of 175 cubic meter capacity at a capital cost of US $ 10.72 million was commissioned in Goa (India) in 1992. The coke rate of the plant is 600 Kg/thm.

6.7 Direct steel making process

Conventionally steel making from iron ore is a two stage process i.e. iron making and then steel making. Attempts are being made to develop a process wherein steel could be produced out of iron ore/coal without converting them to Pig iron as in the case of blast furnace. Such a

process has been classified as direct steel making. RESINESS process is one such process. The name RESINESS combines three metallurgical operations RE-signifies reduction, SIN-signifies sin-tering and ESS-signifies electroslag smelting. This process uses iron ore fines and non coking coal which are preheated to 300 to 350° C. The preheated mixture is charged continuously in an externally heated retort maintained at 1000 to 1020° C to simultaneously reduce the iron ore particles and sinter the reduced iron which is then electroslag smelted to directly produce steel. This technology is at laboratory stage of development.

7.0 Tools for industrial transformation

Apart from the power sector the other coal intensive industries are the iron and steel, cement industry and the pulp & paper industry. By 2047, the iron and steel industry would produce approximately 8 million tonnes of suspended particulate matter; the cement industry, about 13 million tonnes; and paper and paper board industry, just under a million tonnes. While industrial location would become an important factor in reducing the harmful effects of pollution from industrial sources, for certain industries the development and widespread use of specific technologies would acquire increasing importance. The answer would also lie in promoting a mix of industries that have relatively low impacts of a harmful nature on the environment. In other words, the current trend of dirty industries migrating from the countries of the developed world to those of the developing world cannot possibly continue for a country like India. Much greater efforts will have to be made towards relatively high growth of the services sector so that a larger and larger share of economic output in the country would be provided by services rather than manufacturing. This would need to be a strategic direction that India adopts, because restructuring of the industrial sector is a fairly long term process. It has taken Japan, for instance, a quarter century to alter its industrial structure towards a low energy-intensive mix, even though that country did, of course, show dramatic results in the first few years after the first oil price shock of 1973/74.

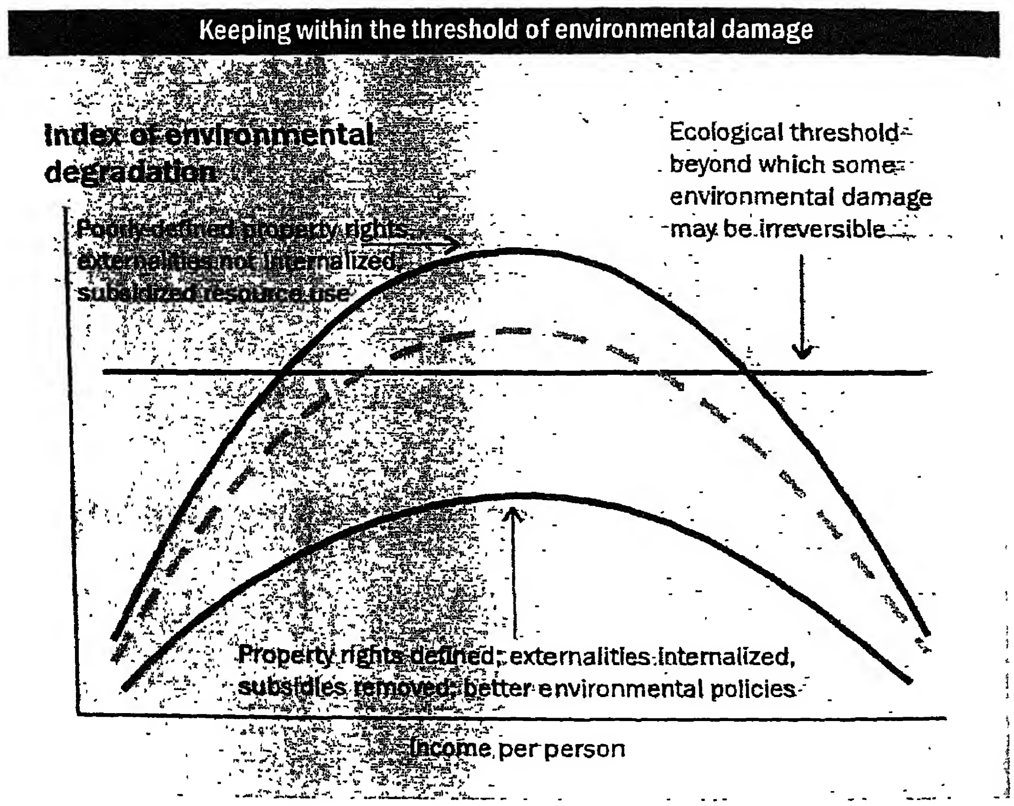
Environmental decision-making has to be merged with the mainstream economic decision-making. Environmental costs, therefore, would need to be internalized effectively, but these costs cannot be estimated uniformly because the severity of environmental impacts varies substantially from location to location, both in physical as well as economic terms. In most of the countries where environmental standards have been effectively set and enforced, local conditions have been paramount in providing a rationale for such standards. In essence, what India and other countries in the region have to seek is the lowest possible environmental Kuznets curve. If appropriate cultural institutional, technological, and political conditions exist, then countries like India can move along the lowest possible curve, distinct from the record of the developed countries.

7.1 Environmental indicators

Development of environmental (air, water, land, social) indicators for evaluation of performances in mines, power generation, steel production may be considered.

7.2 Environmental Kuznets Curves

During the process of industrialization, materials and energy consumption as well as emissions and ambient air concentrations, may follow an inverted-U curve with respect to income (first rising levels of substance flows per unit of income, later in absolute terms). For pollution, this has been called the Environmental Kuznets Curve. Evidence for such patterns have been found on a case study basis for several materials and pollutants, as well as for energy, but almost solely for developed economies. The reasons given for such patterns given are quite diverse , and different research groups emphasize different elements but more efforts may be undertaken to fully understand the driving forces behind the observed inverted-U curve.



Studies on Asia (ADB, 1997) throw light on this in a different way. Much of Asia's environmental degradation took place and accelerated during the region's rapid economic growth of the past 30 years, and during the next 20 to 30 years environmental quality will improve slowly in East Asia and in the higher income countries of Southeast Asia and will continue to deteriorate in South Asia and the lower-income countries of Southeast Asia.

Also, for certain pollutants, such as sulfur dioxide, heavy particles, and fecal coliform in rivers, there appear to be important differences in the income-environment relationship between Asia and the rest of the world. In Asia certain types of pollution tend to rise more rapidly with higher income than they do elsewhere, but they also begin to fall more quickly. Higher initial population density together with more rapid industrialization may account for

the rapid rise, while increased environmental awareness and the availability of new abatement technology permit pollution to be reduced at relatively lower income levels.

However, certain questions need to be explored, which include, are these observed relationships between income and the environment inevitable? Must a worsening environment always accompany economic growth or can the environmental Kuznets curve be flattened?

Key elements of the future waste management infrastructure involve industry, government, and the consumer. Within the firm, consumable products should be designed for safe dissipative use, and service products should be designed for easy disassembly and recycling. Governments should re-align responsibilities, encouraging leasing and other mechanisms, to ensure that producers have incentives to design products for lower life-cycle environmental impacts.

7.3 Enlightened governance and policy-making

This requires a shift in the very concept of governance, which is not fully realized by the current political system or officialdom in India. Given the enormous variation in local conditions in different parts of the country, environmental standards, and norms have to be set specific to each location, and therefore, they must have the full participation of the local people. Action to implement long term solutions would, therefore, also require partnership with and participation of local people and institutions.

7.4 Material flow and balance analysis

Materials flow studies reveal structure, and webs of economic and material relationships among actors, in the industrial system as they map the flow of natural resources into processing and manufacturing industries and the fate of products and wastes existing in them. The object for study can be the mass of individual chemical elements, compounds, or entire classes of materials. The framework for such studies include individual facilities, whole industrial sectors, and geographic regions.

For more comprehensive studies of sectors identified are - coal, iron and steel and cement. However, this should not be considered as a final list as it has been selected based on major coal consuming sectors. Consideration of these sectors begins with the amount the nations consumes, goes on to how much escapes from processing, and ends with whether the escape matters, the toxicity of the element.

7.5 Industrial ecology

A crucial goal of industrial ecology is to develop sustained dynamic of technological improvement. Progress is being made in planning, designing, and implementing industrial ecology systems where the goal is to close the loop to achieve near-zero waste. In the production of consumer products, engineers applying a systems approach as they optimize

individual processes and integrate subsystems with megasystems. The recognition that participation in this process makes good business sense is a motivating factor.

Several different strategies for companies focusing on environmental aspects have been defined. They form the basis of research that one would label as industrial ecology. Most of the research conducted under the heading of eco-efficiency is applied and relatively technical. When this research is more closely connected to the social sciences and policy analysis, three problems arise.

The first is related to the question why do profitable pollution prevention opportunities continue to exist in many companies, often for decades? Similarly in the area of energy conservation, substantial opportunities to reduce energy consumption there exists a big Energy-efficiency gap. The efficiency gap has been explained in terms of high information costs, sensitivity to high investment costs and liquidity constraints, bounded rationality, and principal-agent problems.

A second related problem is that the design of an effective environmental policy crucially depends on a better understanding of when and to what degree companies will implement eco-efficiency. Research is needed into what makes industry moves, i.e. into the incentive structures. Eco-efficiency is probably not driven by cost-reduction opportunities, but by the conscious effort of company management to improve the environmental image and avoid regulatory burdens and future liability. Policy options for the promotion of eco-efficiency range from providing information to instituting eco-taxes.

The third problem is related to the overall environmental success that pollution prevention and related strategies can provide. Pollution prevention advocates have traditionally focussed on success stories. These case studies help to stimulate the interest of industry, but they do not provide policy makers with insight into the potential role of each eco-efficiency strategy in environmental policy. Also, a better understanding of how and how much eco-efficiency can reduce pollution is needed to develop policies that can support the implementation of the strategies. The assessment of the effectiveness of eco-efficiency requires two elements, a model and understanding of firm decision making and the ability to assess and compare the overall pollution of industry.

The sectors discussed in the writing are closely interwoven - coal, power, steel and other industrial sectors like cement. The wastes generated from the power plants and the steel plants can be effectively utilized in various industries

7.5.1 Future mining technologies

In excavation and transportation front, major thrust should be given on Introduction of inpit crushing and conveying system, surface minor for selective mining, high capacity dragline to cater higher stripping ratio, electric wheel, high capacity truck haulage system. For drilling, electric discharge blasting where compressed electric energy is discharged to very high voltage is from electrode for breaking rock. Pit surveying should be conducted using the techniques of GPS (global positioning system) and automated field instruments. Cross pit and around the pit conveying system along with continuous spreading operation interfaced with excavators is required for proper dump management. Central despatch database, a maintenance management system (MMS), is interfaced through a common protocol to provide online expert system for continuous control maintenance of machine health. Major

thrust should be given on introduction of information technology for complete networking of activities. Radio transmission and computer interface compatibility throughout the mine by total mine system integration (TMSI).

7.5.2 *Methane extraction from in situ coal bed*

It is recognized that methane can be produced from virgin coal seams independently from coal mining operation. Methane retains in the coal seam in one of the three possible ways namely adsorbed form on the internal surface of coal matrix, as free gas within pores and fractures, and as dissolved gas in formation waters. The co-occupance of methane in coal depends on coal rank, type of organic matter, temperature, time of burial and maceral composition. It is established that greatest amount of methane in a particular rank of coal is generated in the medium volatile and low bituminous ranges. Coal seams having vitrinite reflectance range of 0.7 to 1.7% and available between the depth range of 300-1200 m are most suitable for commercial production of coal bed methane. The reserve of such type of coals in India are about 29 billion tonne and are mostly located in the coalfields of Damodar-Koel valley. There is a broad estimate of coalbed methane resources to be of the order of 850 billion cu.m.

Various economic and legal issues related to coalbed methane need to be addressed before entering into large scale production of coalbed methane in India. Some major issues are economic viability, tax incentives, legal issues, and marketing. Coal, is a separate mineral resource and at the same time sources for methane gas. Issue needs to be sorted out whether the right for coal and gas should be separately held and necessary legislation need to be passed.

Since coalbed methane exploration and exploitation are very costly process, it needs to work out the economic viability and introduce some kinds of financial incentives to attract the company into venture. Market availability need to be established and ensured before going for any investment.

7.6 Dematerialisation

Materials substitution is considers a principal factor in the theory of dematerialisation. The theory asserts that as a nation becomes more affluent the mass of materials required to satisfy new or growing economic functions diminishes over time. The complementary concept of decarbonisation, or the diminishing mass of carbon released per unit of energy production over time, is both more readily examined and has been amply demonstrated by researchers over the past two decades. For materials in general, several forms of innovation (more efficient recovery of minerals and metals from crude ores, imbuing materials with improved properties per unit mass; and better societal mechanisms for handling and reusing wastes) drive this purported phenomenon. Dematerialisation is advantageous only if using less stuff accompanies or at least leaves unchanged lifetime, waste in processing, and waste in acquisition.

7.7 Pollution prevention

Pollution prevention focuses on process optimization, input substitution and better housekeeping measures. Some of the important source reduction practices are: (a) Equipment modernization and modification, (b) Improved maintenance, © Improved operation practices, (d) Inventory control, (e) Process and/or product modification, (f) Substitution of inputs, (g) In-process recycling.

The issues of discussion are how feasible are these measures, the potential and implementation strategies for reducing the emissions from industries. The environmental management systems adopted by the industries/corporates play a major role in this direction.

7.8 Life cycle analysis

LCA has been defined as a way to "evaluate the environmental effects associated with any given industrial activity from the initial gathering of raw materials from the earth until the point at which all residuals are returned to the earth."

Life cycle assessment of analysis (LCA) is an important tool for eco-efficiency The aim of LCA is to provide information about environmental impacts in production, use, and disposal of different products. The development of LCA was prompted by the desire to avoid shifting pollution in different life cycle stages when minimizing pollution at the specific stage.

The question is how to accomplish the tasks of transforming pollution from one stage to another stage, and how to ensure proper control at source or safe handling of waste/pollution to minimize the adverse affects. It becomes very important in the context of greater dependence on especially coal, because of its associated pollution problems and the limitations posed by the technologies in minimizing the emissions into atmosphere.

Study of life cycle analysis (LCA) to understand the environmental impacts at different stages of coal cycle.

7.9 Environmental management systems

Corporate ecological control can be an effective tool for environmental management. The first step in corporate ecological control is to analyze all current activities in production must be identified, and an ecological balance must be developed. In an ecological balance, the inputs of raw and processed materials are compared quantitatively with the resulting products and emissions, including waste materials, waste water, fumes, waste heat and noise. To make the data useful for company decision-making, the data must be systematically processed and assessed for relevance to environmental issues. The result is a "weakness analysis," which forms the basis for formulating ecologically oriented company objectives as well as for establishing concrete remedial measures. Weakness analysis is designed to help a company identify and assess alternative products, technologies, processing materials, and production methods.

An essential part of corporate ecological control, which is an ongoing process, is the constant scrutiny of measures adopted earlier. Advances in ecological research may reveal that well-intended modification or substitutions have larger environmental effects than were earlier understood.

A proper ecological balance will identify and assess as many environmental effects as possible relating to industrial activities.

7.10 Institutional aspects

Major economic reforms were initiated by the GOI in 1991 with emphasis on privatization and removal of bureaucratic hurdles like licensing and determination of capacities. Significant reforms were also carried out in the financial sector to allow Direct Foreign Investment.

Reforms in the coal sector.

The coal mines nationalisation act 1973 was amended in the year 1993 to allow for captive mining in the power and steel sectors by the private sector. The Amendment also permits setting of washery for coal washing by the private sector. Further amendment took place in 1996 to allow captive mining in the cement sector. About 71 coal blocks have been identified for captive mining estimated to have a reserve of 20,000 million tons. The captive mining experiment has not been successful for various reasons. Some of the important ones are indicated here below:

- Captives mines are debarred from selling the coal to other consumers.
- The captive mine owners had to depend on railways for shipment of coal to the plants for consumption.
- Land acquisition was costly and a time consuming activity
- The size of many of the coal blocks allocated was not economical for profitable mining

Further amendments are being considered to remove the barriers indicated above The government is also planning to set-up a regulatory body to perform the appellate function resolving price disputes between producers and consumers.

The government has made significant investments in the welfare of the mining workers. Approximately Rs 10,000 to 15,000 crores has been invested in providing welfare facilities like housing, medical and safety. Significant skill up-gradation has taken place among the workers in the open cast mines. However, the skill levels in under ground mines remain pathetically low. The welfare programmes has brought about a marked reduction in the accident rates and has improved the living standards of the workers.

Reforms in the Power sector:

Electricity is the costliest form of energy. At the point of delivery to the consumer, the ratio between the amount of energy delivered and the fuel energy required to produce it is some 25 to 30 percent. The main objective on the energy supply side is to develop power generation technologies that raise the efficiency of existing power generation plants. Upgrading T&D facilities can also result in significant energy savings. Better metering

systems, modern billing techniques, and more stringent collection of electricity charges would also improve matters. Price is a major determinant of electricity demand and end-use efficiency. Overall, however, policy makers' appreciation that prices below true opportunity costs lead to wasteful electricity consumption is inadequate.

In recent years, many governments in both industrial and developing countries have introduced reforms in their power sectors. Most East-Asian countries have invited the private sector to invest in power projects. Participation by independent power producers is only an intermediate step, however. Power utilities themselves should shift to private hands. The privatization of electricity generation should be a critical goal for all Asian governments, but its success depends on effective regulation. The process must be transparent, enabling interested parties and the public to identify the basis for the regulator's decision. Effective regulation must also be insulated from political influence to prevent special interests from controlling government decisions. Such steps, together with maintaining a stable political climate, are essential if private financing of energy investments is to be maximized.

Privatization must be accompanied by the most important reform in the energy sector the removal of subsidies, both explicit and implicit. Policy makers should supplement the removal of energy price distortions by introducing fiscal policy reforms that encourage investment in renewable forms of energy.

8.0 Conclusion

The Asian economies are poised for a high growth rate and with the current population well in excess of 3 billion, the production and utilization of energy will remain one of the major development challenges for Asia with coal playing a major role for years to come. The region has undergone enormous changes over the past decade in terms of growth and consumption patterns including a sharply increased reliance on various sources of energy While this increased use of energy has undoubtedly improved the standard of living for many people in the region, it has however left its mark on the environment. This paper has tried to identify a research agenda based on major thrust areas for high growth rate and the threat to the environment.

The increased awareness by the Asian countries of the potentially negative consequences of current patterns of energy use has prompted a reassessment of the country energy strategies which are currently in force. It has become clear that the issue of energy production and utilization can no longer be considered in isolation from the broader concern of sustainable human development. As a result there is a need for a more thorough analysis of the trade-offs between the supply of energy at affordable prices and overall environmental quality The well-being of current as well as future generations will need to be factored into energy strategies and policies.

References

Pachauri, R.K., "Looking back to think ahead", GREEN India 2047. New Delhi: Tata Energy Research Institute (In press)

Mathur, A., Hasan, S., Dadhich, P., "Evaluation of Clean Coal Technologies", Report submitted to Central Pollution Control Board", New Delhi (January, 1998)

Tata Energy Research Institute & National Physical Laboratory. "Asia Least-cost Greenhouse Gas Abatement Strategy - ALGAS support for the Government of India" (February, 1998)

Chadwick, M.J., Highton, N.H., Lindman, N., "Environmental Impacts of Coal Mining and Utilization", Pergaman Press 1987

Rao O.P., "Technologies for utilisation of high ash coals - Indian perspective"(pp 75-85) international conference Asia Energy Vision 2020 Sustainable Energy Supply (Nov 15-17, 1996): organised by World Energy Council and The Institution of Engineers (India).

Silvio J. Flaim, Ellis Jera, "Environmental Consequences of Renewable Energy Development in Rural India", pp. 24-35 in "Rural and Renewable energy perspectives from developing countries", TERI (1997) edited by Venkata Ramana P

Greedy, D.P., "The Feasibility of Coalbed Methane Projects in India", pp 126-200. BIMI '96, New Delhi 16-18, 1996

Asian Development Bank, 1993, Environmental Issues related to electric power generation projects in India, March 4-6, 1993, Jaipur, India, organised by TERI, New Delhi.

IHDP, May 1997, Industrial Transformation (An inventory of Research), IHDP-IT No.8.

R Socolow, C Andrews, F Berkhout and V Thomas (Ed.), 1994, Industrial Ecology and Global Change. Cambridge: Cambridge University Press.

Buskies, U., Krupp Koppers Gmbh, "The Efficiency of Coal-Fired Combined Cycle Powerplants", Applied Thermal Engineering Vol. 16, No. 12, pp.959-974, 1996

Foster-Pegg, R.W., "Combined cycle have potential for cleaner, more economical use of coal", POWER ENGINEERING, pp. 80-84, April 1982

Kjaer, S., "Coaldust-fired Power Station Unit with advanced Water/Steam process, Report no. EP 90-03, Power Station Engineering, Oct. 1990

Todd, M Douglas-GE Company, Joiner, M James-Fluor Daniel, Inc., "IGCC Cost Study"

Koenders, L.O.M, Zuideveld, L.P, "The Shell Coal Gasification Process", Shell Internationale Petroleum Masstschappij B.V., Sept. 1995

Greenhouse Gas Emissions From Power Stations-A report produced by the IEA Greenhouse Gas R&D Programme, United Kingdom

Abbi, Y.P, Ghosh, A.K., "Clean Coal Technologies for Power Generation", Presented at Asia Energy Vision 2020, Organized by WEC and the Institution of Engineers (India), Nov. 15-17, 1996

Gas Turbine Engineering Handbook, by Meherwan P. Boyce, President, Boyce Engineering International, Inc., Gulf Publishing Company, Jan. 1992

Energy Technology Characterization Handbook Environmental Pollution and Factors, Third Edition, March 1983, U.S. Department of Energy, Washington, D.C. 20545

McMullan, J.T., Williams, B.C., Sloan, E.P., "Clean coal technologies", published in the proceedings of Institution of Mechanical Engineers, Vol 211, Part A, 1997

Chapter 11

Dematerialisation and rematerialisation

Two sides of the same coin

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Key words materials consumption, energy use, economic development, evolutionary economics

Abstract The thesis that a 'de-linking' occurs between materials use and economic growth during economic development (the so-called 'dematerialisation hypothesis') is discussed. This chapter argues that dematerialisation is not a persistent trend in industrialised economies, but occurs during periods of rapid structural and technological change. Evidence suggests that periods of 'rematerialisation', when materials use is re-linked with economic growth, follow periods of dematerialisation. A theoretical explanation based on the idea of evolutionary patterns in materials use is proposed.

1. INTRODUCTION

The use of materials and energy undoubtedly has economic origins and environmental consequences. The consumption of materials and energy is therefore an important interface between the economy and the environment and analysis of the patterns, causes and effects of materials and energy consumption have gained considerable interest in environmental economics. Such analysis can be conducted on the level of individual products, firms or nations. The latter orientation has resulted in empirical work investigating the 'stylised facts' of the consumption of materials and energy as the economy of a country develops. One of the positions that has been put forward is that in the process of on-going economic growth the economy is 'de-linked' from its resource base, so that rising per capita incomes would be associated with a declining consumption of resources and associated

pollution. It is nowadays common to depict the relationship between resource use and income as an inverted-U curve; this implies rising levels of resource use in early stages of economic development, but declining resource use in subsequent stages. With growing environmental awareness, this process of dematerialisation (and 'de-pollution') has received considerable scientific and political interest. After all, the implication of an inverted-U curve between resource use and economic development would imply that economic growth might be compatible with improvements in environmental quality.

This chapter discusses the stylised facts about resource consumption and its relationship to economic development and economic growth Sections 2 and 3 provide a historical overview of the various contributions in the literature since the beginning of the 1960s on the patterns of resource consumption in combination with their environmental consequences They show that some partial evidence that the inverted-U curve may not represent the actual development of aggregated throughput exists The evidence shows that an N-shaped curve is more likely (similar to the inverted-U curve but with a subsequent increase in resource use for developed economies). Section 4 assesses the factors underlying the changes in resource use and Section 5 discusses how these factors determine the throughput-income relationship over time. It will be argued that recent advances in economic theory do suggest that N-shaped patterns occur. The policy as well as the scientific implications of these findings will be discussed in the concluding Section 6.

2. FROM LIMITS TO GROWTH TO THE INTENSITY OF USE HYPOTHESIS

Until the late 1960s, the consumption of materials, energy and natural resources was believed to grow at the rate of economic growth. This gave rise to growing concerns about the earths' natural resource availability, which was most firmly put forward by the Club of Rome's "Limits to Growth" study (Meadows et al., 1972). This report predicted a linear and rather deterministic relationship between economic output and material input Because of world-wide economic growth, mankind is likely to face widespread resource exhaustion, which in turn would negatively affect economic and population growth, human health and welfare.

The arguments put forward by the Club of Rome can be seen as a restatement of the views of the nineteenth century philosophers Malthus and Ricardo. They predicted that scarcity of natural resources (including land) would eventually result in diminishing social returns to economic efforts

which effectively puts a limit on economic growth. The result would be a steady state, with a constant population, bounded by the carrying capacity of the earth.

The position that economic growth in the long run would be limited by resource scarcity was examined and tackled most forcefully by Barnett and Morse (1973:11). They state: "Advances in fundamental science have made it possible to take advantage of the uniformity of energy/matter, a uniformity that makes it feasible, without preassignable limit, to escape the quantitative constraints imposed by the character of the earth's crust. A limit may exist, but it can be neither defined nor specified in economic terms. Nature imposes particular scarcities, not an inescapable general scarcity". What they hint at is obvious: progress in human knowledge opens up new substitution possibilities and advances the technology of extraction, use and recycling, which ensures that resource scarcity does not become a permanent constraint to economic activities.[1] Simon (1981) has in this respect referred to human knowledge as 'the ultimate resource'.

The 'limits to growth' have not only been disputed in economic theory. Substantial empirical work following the Report to the Club of Rome has found increasing evidence of a 'slackening' of world material demand since the 1970s (Tilton, 1986, 1990). Table 11.1 underlines this development. Between 1951 and 1969 the consumption of most refined metals increased exponentially, annual growth rates were often higher than 5%. A doubling of metals consumption took place every 15 years. Predictions of future demand for materials by Meadows et al. (1972) and Malenbaum (1978) depicted lower but still rather high growth rates for the next decades. However, if these predictions are compared with the actual developments of the world materials demand we see what statisticians would call 'a break in series'. World growth rates of metals between 1973 and 1988 have approximated a modest 1% per annum. A doubling of consumption would then occur only every 70 years.

Table 1 Annual world growth rates in the consumption of refined metals

	Actual[iii] 1951-69	Meadows[ii] 1971-	Malenbaum[i] 1975-85	Actual[iv] 1973-88
Iron ore	6.2	1.8	3.0	0.8
Copper	4.7	4.6	2.9	1.2
Aluminium	9.2	6.4	4.2	1.7
Zinc	4.9	2.9	3.3	0.7
Tin	1.7	1.1	2.1	-0.5
Nickel	5.0	3.4	3.1	1.7
GDP	4.8	NA	3.5	3.0

Sources: [i] Malenbaum (1978), [ii] From Meadows (1972), mean estimations from the US Bureau of Mines, [iii] From Tilton (1990), [iv] GDP Estimation based on UN, Statistical Yearbook, metals World Resources Institute (1990) 'World Resources 1990-1991'

Explanations for the slackening of world materials demand were first put forward by Malenbaum (1978) in a theoretical sketch which has later become known as the 'intensity of use hypothesis'. According to Malenbaum, the demand for materials is derived from the demand for final goods; consumer durables such as automobiles and disposables such as beer cans. Since material costs form only a small proportion of the total costs of these products, the prices of materials have an insignificant influence on demand. Instead, income is the explanatory factor in materials consumption Malenbaum predicted non-uniform income elasticities over time and across countries because of the different characteristics of the composition of final demand associated with different stages of economic development. Developing countries with an economic structure relying on subsistence farming typically have a low level of materials and energy consumption. However, as industrialisation takes off, countries specialise first on heavy industries to satisfy consumer demand for consumer durables, such as houses, and infrastructure, and therefore materials consumption increases at a faster rate than income. The subsequent induced shift towards service sectors will result in an associated decline in the demand for materials. Hence Malenbaum depicts the relationship between materials demand and income as an inverted-U-shaped curve (the line IUS in Figure1 with the turning point at a).[2] Technological change has the effect of shifting the relationship between materials demand and income downwards since technological improvements in materials processing, product design and product development implies that the same economic value can be generated with less material input (the line IUS' in Figure 11.1). Late developing countries therefore follow a less materials-intensive development trajectory

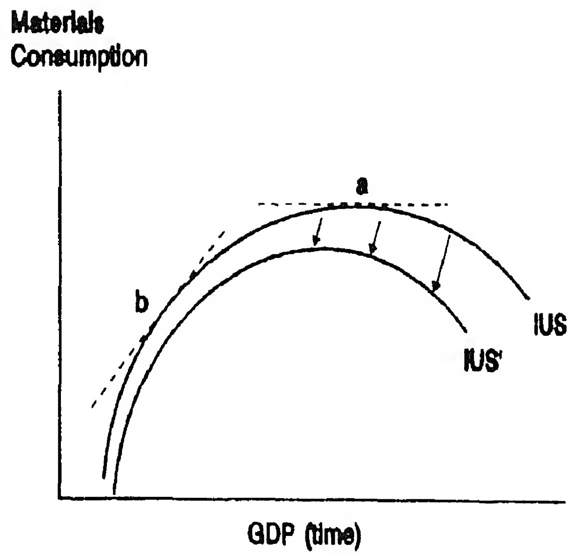


Figure 1 The 'intensity of use' hypothesis and the influence of technological change

3. CONTINUING DEMATERIALISATION?

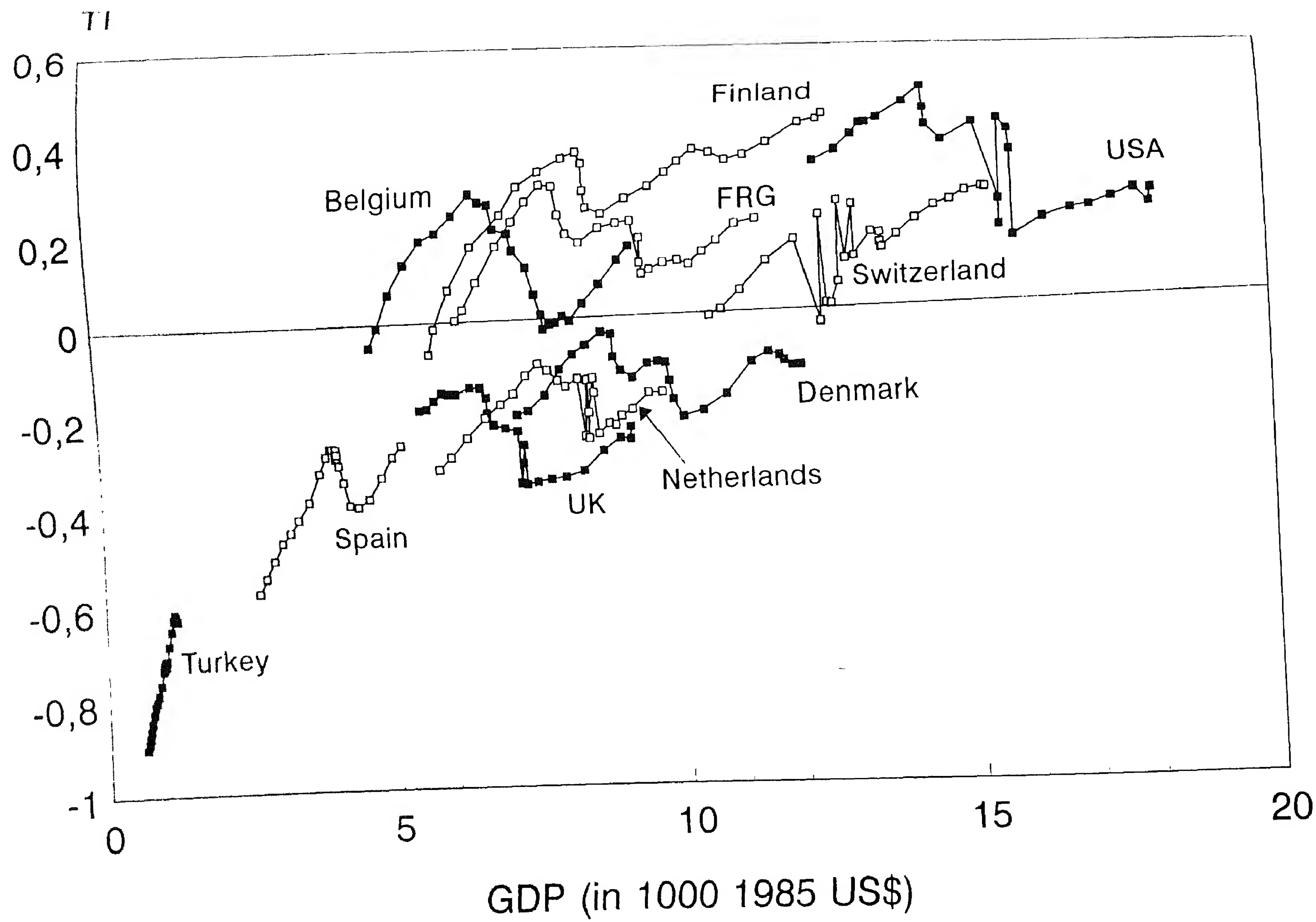
The 'intensity of use' hypothesis has been found to hold in a number of case-studies for specific materials and energy (cf. Bossanyi, 1979, Chesshire, 1986, Williams et al., 1986; Tilton, 1990, Valdes 1990, Goldemberg, 1992; Nilsson, 1993). These show that dematerialisation, defined here as a reduction in energy and materials consumption, has occurred in a wide range of developed countries. But Labys and Wadell (1988) have suggested that such conclusions can be misleading They argue that dematerialisation may more adequately be described as 'transmaterialisation' The demand for materials typically follows a Schumpeterian life-cycle from introduction, via growth and maturity, to saturation and decline. Whereas the intensities of copper and iron ore in the US economy peaked during the 1940s, new peaks are currently recorded for polyethylene, platinum and ceramics Because the collection of statistics for the consumption of new materials lags behind in the introduction and growth-stages, studies using statistical data often observe the saturation and decline stage of materials demand which may not reflect overall dematerialisation but rather materials substitution, or transmaterialisation.

Whereas transmaterialisation may be a purely descriptive phenomenon in resource economics, the environmental implications are not neutral.

Resource consumption has consequences for the environment by virtue of the mass balance principle (Ayres and Kneese, 1969). There would be no reason to assume that environmental pressure decreases due to dematerialisation if only the composition of the materials and energy consumed changes but not the absolute level. Moreover, due to transmaterialisation new substances may enter the environment with serious negative impacts. For example, the impacts of DDT, CFCs and PCBs on human health and the environment were understood long after their market introduction.

Therefore, environmental economists have been investigating ways to construct indicators that represent a better overall picture of the pressure materials and energy consumption exert on the environment. Such indicators may be indicative of the "throughput" of the economy, defined by Daly (1991: 36) as the (entropic) physical flow of matter and energy from nature's sources, through the human economy and back to nature's sinks. A crucial issue in the construction of a throughput-indicator is how to add the various types of materials and energy into a single and uniform indicator. Several methods have been proposed, all of which may be critical to the results of empirical applications. For example, Moll (1993) investigates dematerialisation developments for several materials together in the US economy and finds that when aggregated over mass, the US economy dematerialises after 1970. But when aggregated over volume (in m^3) no dematerialisation trend can be found. Moll defends the use of aggregation over volume with the notion that mass in itself does not represent a function to consumers. Other aggregation schemes that have been proposed are: 'net energy' and entropy (Ayres and Schmidt-Bleek, 1993).

A more simplified method of aggregation has been employed by Jänicke et al. (1989) who investigated the developments of throughput in 31 OECD and communist economies between 1970 and 1985, where throughput has been defined as the equally weighted level of energy consumption, steel consumption, cement production and weight of freight transport on rail and road (as a general measure of the volume aspect of an economy)[3]. These proxies of throughput may capture to a large extent the environmentally relevant physical realities of the economies under investigation The results of this analysis are given in Figure 11.2 where the arrows give the linearised developments between 1970 and 1985 for various countries. They show a development that confirms the earlier analysis by Malenbaum: rising levels of throughput in less developed economies and decreasing levels of throughput for the more prosperous countries. This figure suggests that dematerialisation also holds for a more comprehensive set of matter/energy flows and it has been interpreted by some commentators as 'a sign of hope' in resolving current environmental problems (cf. Wieringa et al, 1991; Simonis, 1994; von Weiszäcker and Schmidt-Bleek, 1994).



TI
0,6
0,4
0,2
0
-0,2
-0,4
-0,6
-0,8
-1
0
5
10
15
20
GDP (in 1000 1985 US$)
Finland
USA
Belgium
FRG
Switzerland
Denmark
Netherlands
UK
Spain
Turkey

Figure 2. Developments in aggregated throughput Arrows indicate the linearised development between 1970 and 1985. From Weiszäcker and Schmidt-Bleek (1994) after Jänicke et al (1989)

The results of Jänicke et al. have been re-examined by De Bruyn and Opschoor (1997) by extending the time-horizon and making some minor improvements in the indicator calculation. Their results suggest that since 1985 there has been an upswing in the levels of throughput for some developed economies. Figure 11.3 makes this development explicit for 8 countries between 1966 and 1990. Using the same indicators as Jänicke et al. (1989) we see that the developed economies experienced an increase in their levels of throughput again after 1985. A phase of dematerialisation existed for all countries except Turkey between 1973 and 1985, but this did not continue in the late 1980s. De Bruyn and Opschoor hence conclude that the actual pattern of throughput over time may be more adequately described as N-shaped, similar to the inverted-U shaped curve but with a subsequent phase of 'rematerialisation' that may continue until new technological breakthroughs enable another de-linking phase[4]

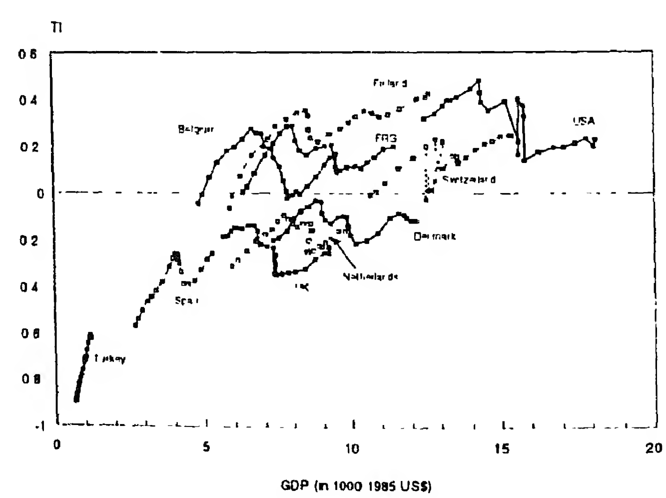


Figure 3 Developments in aggregated throughput Every dot indicates the one years moving average between 1966-1990

These findings may also have consequences for the environment in developed economies. Some empirical work has suggested that there exists an inverted-U, or environmental Kuznets, curve between several pollutants and income (cf Selden and Song, 1994; Grossman and Krueger, 1995). Given the fact that emissions and wastes originate from the consumption of materials and energy, it can be expected that some pollutants would follow a similar N-curve as described above. Investigations into the patterns of CO_2, NO_x and SO_2 emissions in some developed economies indeed reveals that CO_2 emissions rise after 1985 (De Bruyn et al., 1996). The observation that SO_2 emissions decline may relate to the relatively less expensive costs of abatement and higher local benefits for the communities living in polluted areas (health and forest vitality) Also the international negotiations dealing with the reduction of SO_2 emissions are in a more advanced stage than those dealing with CO_2 emissions

4. THE IMPORTANCE OF STRUCTURAL AND TECHNOLOGICAL SHIFTS FOR DEMATERIALISATION

The underlying causes of the throughput patterns have not thus far been adequately and concisely investigated in empirical research. A fairly simple model can clarify which factors are important for the changes in material demand Notice first that material demand I_t can be related to income Y_t in the following way:

$$I_t = U_t \cdot Y_t \qquad \text{equation 1}$$

where material demand is the product of the intensity of use U_t ($=I_t/Y_t$) and the level of income Over time, material demand will hence be influenced by the changes in both variables, as given in (2)

$$\frac{dI}{dt} = Y_t\frac{dU}{dt} + U_t\frac{dY}{dt} \qquad \text{equation 2}$$

Hence, economic growth (d_Y/d_t) will result in a higher material demand if the intensity of use remains the same ($d_U/d_t=0$) Dematerialisation ($d_I/d_t<0$) will occur if the intensity of use declines at a higher rate than the rate of income growth. If, at a certain point in time, the rate of economic growth overtakes the decline in the intensity of use, the economy starts to re-materialise again

A minimum condition for dematerialisation, and the occurrence of an inverted-U shaped curve, is that the intensity of use declines. The intensity of use can be perceived as a kind of efficiency criterion: the amount of materials that are required to 'generate' a certain level of income. Alternatively one may speak of 'material productivity', analogous to the more well-known concept of labour productivity. The total material productivity of an economy will be determined by the efficiency of material use at the level of production processes, products and the consumers. These different levels can be distinguished using the following identity (cf. Roberts, 1990; Tilton, 1986):

$$\underset{IU}{\frac{I_t}{Y_t}} = \underset{EST}{\frac{I_t}{P_t}} \cdot \underset{MCP}{\frac{P_t}{Q_t}} \cdot \underset{PCI}{\frac{Q_t}{Y_t}} \qquad \text{equation 3}$$

where P_t is the mass of materials that is embodied in products and Q_t the number of products. The total material productivity of an economy, the intensity of use, is hence a function of three efficiency ratios. The first ratio, the efficiency state of technology (EST), defines the efficiency of the production technology as the ratio between the mass input in the production process and the mass embodied in the products. If the efficiency of the process technology improves, more materials will be embodied in the products and fewer materials will be wasted during the production process. This will lower the EST and hence decrease the IU. Process innovation is an important driving force of the EST.

The second ratio gives the material composition of products (MCP) and it relates the mass of materials embodied in the products to the number of products produced. The MCP defines the material productivity at the level of the products. Dematerialisation of products implies that less materials are embodied in the same product, which has occurred for example in US manufactured automobiles (Herman et al., 1989) or computers. Dematerialisation of products implies that material is used more efficiently to generate the same product-services to the consumers. Product innovation is an important factor for the decline of the MCP.

The third ratio defines the material productivity at the level of the consumers. It can be perceived as the amount of income spent on (physical) products. Less income spent on material products and more on non-material services implies that the material productivity will increase. This may be achieved due to a change in the structure of final demand (referred to as structural or inter-sectoral changes) or due to increases in the value added of individual products. Adding more knowledge to existing products (such as

computers) will increase their value added and lower the product composition of income (PCI)

The changes in the intensity of use over time thus depend on the development of the process technology, product innovation and changes in consumer preferences. How do these factors relate to the inverted-U and N-shaped patterns that have been discussed in the previous section? One could argue, following Malenbaum, that the change in the consumer preferences and the associated change in the structure of production is the main determinant of the inverted-U shaped curve It does make sense to assume that people in developing countries first show an appetite for material welfare (cars, infrastructure, consumer durables) which increases total material consumption and that only at certain high income levels do services (banking, insurance, recreation) become more important

The importance of the PCI as the underlying cause of the change in the intensity of use makes it difficult to explain the N-shaped pattern. The idea that consumers, in the course of economic development, should reverse their preferences is untenable from a theoretical perspective as well as from an intuitive point of view. Consumers probably do not start to prefer material consumption goods again after a period in which they preferred more services. Does this imply that the N-shaped pattern is unsupported by economic theory?

5. AN EVOLUTIONARY PERSPECTIVE ON DEMATERIALISATION

Previous empirical work has decomposed the change in energy intensities into structural (intersectoral) and technological factors Howarth et al (1991), for example, decomposed the change in energy intensities for eight OECD economies and found, on average, little support for structural changes as an important determinant of the recorded decreases in the energy intensities between 1973 and 1988. The decreases in energy intensities are much better explained by technological improvements in processes and product innovations. These conclusions seem to hold generally for a range of developed economies, a finding confirmed by other studies

If structural changes in developed economies do not have a marked impact on materials intensities, this implies that the PCI is not the main factor that determines material demand This need not contradict the inverted-U shaped curve since total aggregate throughput could still decrease if decreases in materials intensities due to technological improvements are faster than the rate of economic growth If the decrease in the intensity of use has come to a halt, economic growth will simply result

in higher levels of throughput, as can be seen from equation 2. This would imply an N-shaped curve. If we accept the fact that structural changes play a minor role in the development of the intensities for developed economies, the main question concerning the explanation for the different patterns deals with the issue of how technology will develop over time. Conflicting views exist on this in economic theory.

In neoclassical economic theory technological change follows a process of Darwinian natural selection at the margin. However, why innovations occur has been poorly understood in neoclassical economics. Whereas technological change was first assumed to be 'autonomous' and 'exogenous' to the neoclassical model, more recently the theory of endogenous growth has incorporated technological change by explicitly investigating the role of human knowledge in generating R&D and welfare. Romer (1990), for example, argues that economic growth can be enhanced by investing in 'human capital' that results in innovations and technological change. Whether innovations are rejected or accepted depends on opportunities for the firm to compete more successfully in the market. Technological change is thus endogenised by making it dependent on a cost-benefit analysis concerning investments. The yields of those investments will gradually improve over time because of the accumulation of knowledge. As a logical result, the economy will gradually become less material- and more knowledge intensive.

Alternatively, it has been suggested that the process of technological change does not follow a smooth process along a path of equilibrium, but is characterised by disequilibrium and an evolutionary path of learning and selection (cf. Dosi and Orsenigo, 1988). Innovations over time may typically come in clusters as the result of a process of creative destruction, first introduced by Schumpeter. Gowdy (1994) has analysed the discussion concerning the process of change in biology and argues that biological evolution as a Darwinistic process of gradual adaption is hard to defend by the fossil record. The intermediate steps between various species that would support gradual change are missing. It is here that the 'punctuated equilibrium' view has been introduced: species remain virtually unchanged for quite a long time, but radical breaks in the equilibrium result in sudden appearance and extinction of species. Evolution takes place not so much on an individual level but on a species- or systems-level, where species co-evolve together in their environment. Gowdy then applies these findings to economics and argues that the economic system may be relatively stable and in an equilibrium during certain times which are followed by a drastic shift in technological paradigms and institutional and organisational structures. Hence the evolutionary path of learning and selection may, given sufficient stability in technological paradigms and institutional structures, move around a certain equilibrium (a so called attractor point), but changes in

technological paradigms and institutional structures may shift the attractor point so that in the long run the disequilibrium state is persistent

It is beyond the scope of the present paper to elaborate the arguments, examples and mathematical treatments that underpin this point of view But it is interesting to investigate whether the developments in resource use are characterised by a process involving gradual changes, resulting in lowering intensities of use, or by a process of alternating punctuated equilibria An easy way to present the patterns of the intensity of use over time is to use phase diagrams (cf. Ormerod, 1994, who applied phase diagrams to investigate employment issues). A phase diagram is a scatter diagram where a certain variable is plotted against two dimensions the value in the current year and the value in the previous year The various values of the intensity of use over time are then connected with a line This way of plotting the data has the advantage of illustrating clearly whether there is a gradual improvement in the intensity of use (which would result in a straight negative line) or whether the intensity of use moves around a cycle of punctuated equilibria (or attractor points) As an example we take historical data for steel and energy intensities in the Netherlands

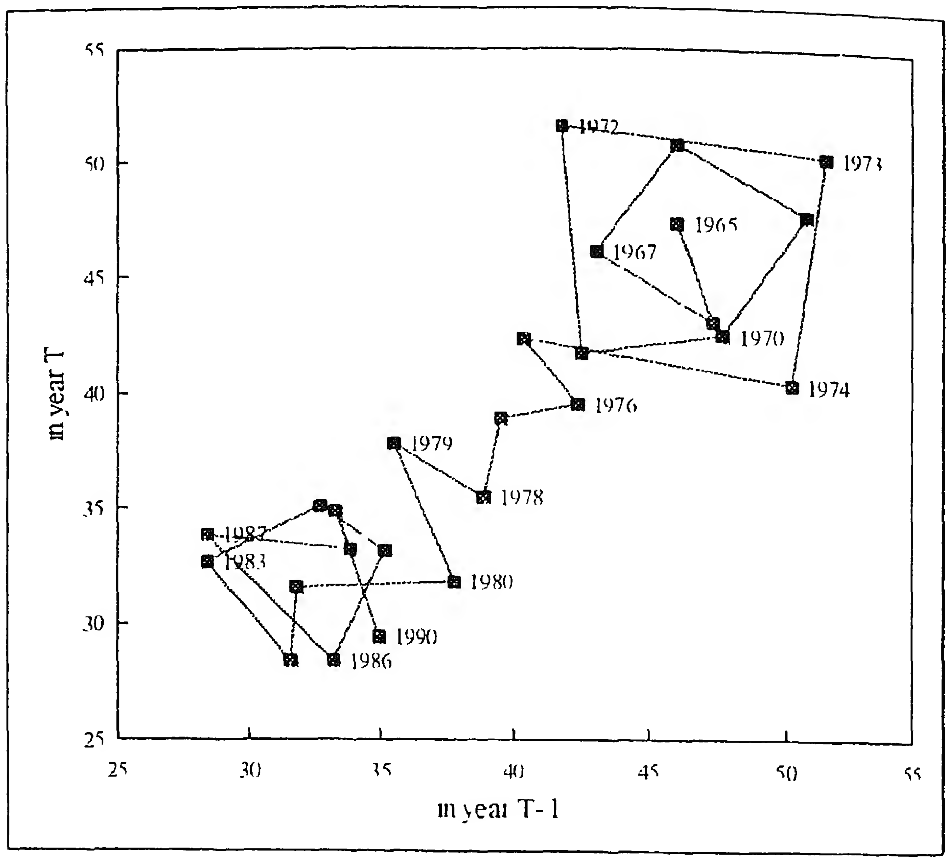


Figure 4 Developments of steel intensities in the Netherlands in (1965-1990) kg/1000 US$ (1985)

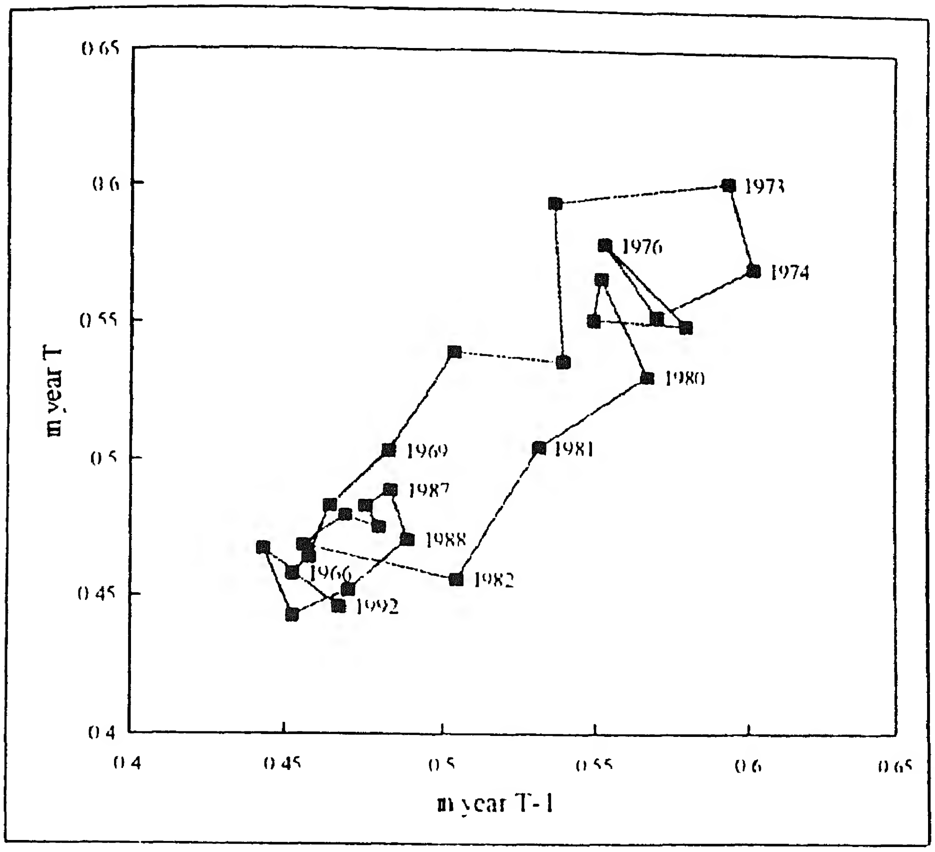


Figure 5 Developments of energy intensities in the Netherlands (1966-1992) :toe/1000$(1985)

Figures 11.4 and 11.5 give the phase diagrams for steel and energy consumption per unit of GDP in the Netherlands, from the mid-1960s until the beginning of the 1990s Both give evidence of a pattern of punctuated equilibria, although the time period investigated may be too short to reveal the evolutionary forces at work. Steel intensity in the Netherlands remains roughly the same between 1966 and 1974, fluctuating around an attractor point of approximately 45 kg per 1000 US$ (1985) After 1975, however, the steel intensity starts to decline, at least until 1982 when a new equilibrium is reached, fluctuating around the 32 kg per 1000 US$ Energy intensities increase monotonically from 1966 to 1973. From the early 1970s to 1979, energy intensities abruptly stop growing and stabilise around an attractor point In 1979 intensities start to decline rapidly, at least until 1983 when a new attractor point has been reached at a level about 20% below the attractor point prevalent in the 1970s.

When these patterns are related to the theory of punctuated equilibria they may imply the following. When the economy is in an equilibrium phase, intensities of materials and energy remain constant and move around a fixed attractor point. These movements are marginal fluctuations that can be described as 'business cycles'. During the time that the intensities remain stable, economic growth has the effect of an equi-proportional increase in the consumption of materials and energy by virtue of equation 2. Hence the equilibrium state of the economy implies that materials consumption and economic growth are linked. However, during times of radical shifts in price structures, or technological and institutional paradigms, intensities will fall and throughput starts to decline, at least until the economy stabilises again around a new attractor point[5]. Then the relationship between economic growth and materials consumption is again positive and the throughput rises again with the same rate as the growth in incomes. The result is a relationship between income and throughput that is N-shaped, as revealed empirically in Section 3.

There is a likelihood that this pattern of punctuated equilibria may also continue in the future. This implies that the current positive linkage between economic growth and materials demand may persist until a shock, defined above as a change in technological paradigms or institutional structures, shifts the relationship temporarily in the other direction. In the long run therefore, rematerialisation may be followed by dematerialisation and vice versa. The long-run relationship between throughput and income in developed economies may be perceived as a saw-pattern. Whether the direction will be sloping downwards or upwards cannot be answered at this stage but there is reason to believe that the trend will be towards higher levels of throughput. If we compare the various countries in Figure 11.3, for example, we still see that higher income countries have higher levels of throughput.

6. DISCUSSION

This chapter has investigated the 'stylised facts' of the consumption of materials and energy during the course of economic development. It has been argued by several authors that the relationship between materials and energy consumption and income would be inverted-U shaped so that after a particular level of income, growing output may be associated with declining (material) input. This phenomenon of dematerialisation has been found in some studies on single materials and energy. However, with a more comprehensive measure of throughput, several developed economies show a phase of rematerialisation since the second half of the 1980s. The resulting

N-shaped pattern can be explained by reference to recent advances in economic theory which suggests that the actual economic process may be better explained by dis-equilibrium, non-stability and evolutionary patterns of learning and selection. During times of radical changes in the technological and institutional paradigms, the relationship between throughput and income growth may be altered due to increased substitution possibilities and technological advances in the processing and use of materials and energy. However, such a phase of dematerialisation will not persist indefinitely, and the positive relationship between income growth and throughput growth is likely to be restored, albeit at a lower level of throughput.

Dematerialisation and rematerialisation may hence be two recurring phenomena in the throughput trajectory of developed economies, two sides of the same coin. The environmental implication is that the often-made argument that economic growth can be beneficial to environmental quality is probably invalid. If the N-shaped figure holds for aggregated material input, a similar development should be traced for aggregated environmentally relevant output (emissions and wastes) by virtue of the mass balance principle. For the policymaker, these results imply that there can be less room for optimism that the process of economic growth itself will solve our environmental problems. Instead, institutional and technological breakthroughs may be required to reverse the current trend of rematerialisation into a more environmentally benign trend. We have observed that in the past these radical changes have occurred in the years characterised by high and rising prices of energy and raw materials. These factors appear to have triggered governments and business enterprises to reconsider their use of resources and the associated environmental impacts and to start a process of rationalisation, or restructuring. A new stage of eco-restructuring, possibly based on steep price rises for materials and energy inputs, may be required to prevent environmental disturbances to result in irreversible impacts and to shift the positive relationship between income growth and throughput growth (temporarily) in a new direction.

REFERENCES:

Auty, R. (1985) Materials intensity of GDP. Research issues on the measurement and explanation of change, Resources Policy, vol11, p275-283

Ayres, R.U. and Kneese, A.V. (1969) Production, Consumption and Externalities. Am. Econ. Review, LIX, 282-297

Barnett, H.J., Morse, Ch., (1973) Scarcity and Growth. The Economics of Natural Resource Availability. John Hopkins University Press, Baltimore

Bossanyi, F., (1979) UK primary energy consumption and the changing structure of final demand. Energy Policy, vol. 7, September, p253-258

Chesshire, J , (1986) An energy-efficient future a strategy for the UK, Energy Policy, vol 14· p395-412
Daly, H.E , (1991) Steady State Economics Second Edition with New Essays Island Press, Washington, DC, 297 pp
De Bruyn, S M , J C.J.M van den Bergh, J.B Opschoor, (1996). Economic Growth and Patterns of Emissions: Reconsidering the Empirical Basis of Environmental Kuznets Curves, Free University Research Memorandum 1996-48
De Bruyn, S M , Opschoor, J B (1997) 'Developments in the throughput-income relationship: theoretical and empirical observations', Ecological Economics 20 255-268
Dosi, G, Orsenigo, L. (1988) Coordination and transformation an overview of structure, behaviours and change in evolutionary environments', In Dosi, G , Freeman, C , Nelson, R , Silverberg, G and Soete, L (Eds), Technical change and economic theory, Pinter Publishers Ltd , London
Georgescu-Roegen, N , (1971) The Entropy Law and the Economic Process Harvard University Press, Cambridge, MA.
Goldemberg, J., (1992) 'Energy, Technology, Development' Ambio, vol 21, p14-17.
Gowdy, John M (1994) Coevolutionary Economics The Economy, Society and the Environment, Dordrecht Kluwer Academic Publishers
Grossman, G M., Krueger, A B , (1995). Economic growth and the environment, Quarterly Journal of Economics 112 353-378
Herman, R , Ardekani, S A , Ausubel, J H , (1989) Dematerialization, in J H Ausubel & H E. Sladovich (Editors) Technology and Environment, National Acadamy Press, Washington, D.C , p50-69
Howarth, R.B , Schipper, L., Duerr, P A , Strum, S [1991] Manufacturing energy use in eight OECD countries Decomposing the impacts of changes in output, industry structure and energy intensity, Energy Economics, p135-142
Janicke M., Monch, H , Ranneberg, T , Simonis, U E , (1989) 'Economic Structure and Environmental Impacts East-West Comparisons' The Environmentalist, vol9, p171-182
Klaassen, G , (1995) Trading sulphur emission reduction commitments in Europe A theoretical and empirical analysis, International Institute for Applied System Analysis (IIASA), Laxenburg, Austria
Labson, B S & Crompton, P L , (1993) Common Trends in Economic Activity and Metals Demand Cointegration and the Intensity of Use Debate Journal of Environmental Economics and Management, vol 25, p147-161
Labys, W C & Wadell, L M , (1989) Commodity lifecycles in US materials demand Resources Policy, vol 15, p238-252
Malenbaum, W., (1978) World Demand for Raw Materials in 1985 and 2000, McGrawhill, New York, 126pp.
Meadows, D H., Meadows, D L , Randers, J , Behrens, W W , (1972) The Limits to Growth, Universe Books, New York
Moll, H C. (1993) Energy counts and materials matter in models for sustainable development dynamic lifecycle modelling as a tool for design and evaluation of long-term environmental strategies, Styx, Groningen, 396pp
Nilsson, L J 1993. Energy intensity trends in 31 industrial and developing countries 1950-1988, Energy, 18 (4). 309-322
Ormerod, P (1994) The Death of Economics. Faber and Faber, London, 230pp
Radetzki, M , Tilton, J E (1990) Conceptual and Methodological Issues, in J E Tilton (Ed) World Metal Demand. Trends and prospects, Resources for the Future, Washington D C., pp 13-34

Roberts, M C (1990) Predicting metal consumption The case of US steel, Resources Policy, vol 16 p56-73
Romer, P M (1990) Endogenous Technological Change, Journal of Political Economy, vol 94 S71-S102
Selden, T M , Song, D S , (1994) Environmental Quality and Development Is There a Kuznets Curve for Air Pollution Emissions? Journal of Environmental Economics and Management, vol 27, p147-162
Simon, J L , (1981) The Ultimate Resource Princeton University Press, Princeton, New Jersey
Simonis U E (1989) Industrial restructuring for Sustainable Development Three points of departure, Science Centre Berlin I S II 89-401, Berlin, 30pp
Simonis, U E (1994) Industrial restructuring in industrial countries, in R U Ayres and U E Simonis (Eds), Industrial Metabolism Restructuring for Sustainable Development UNU Press, New York, pp 3-21
Tilton, J E (1986) Beyond Intensity of Use Materials and Society, vol 10, 245-250
Tilton, J E (1990) The OECD Countries Demand Trend Setters, in J E Tilton (Ed) World Metal Demand Trends and prospects, Resources for the Future, Washington D C , p35-76
Valdes, R M (1990) Modelling Australian steelconsumption, Resources Policy, vol16, p172-183
Weizsaecker E U von, Schmidt-Bleek, F (1994) Signs of hope for the 21st century', in Dutch Committee for Long-Term Environmental Policy (Eds) The Environment Towards a Sustainable Future, Kluwer Academic Publishers, Dordrecht/Boston/London, p21-45
Wieringa, K , H J M de Vries, N J P Hoogervorst, (1991) Economie in Rijksinstituut voor Volksgezondheid en Milieuhygiene, Nationale Milieuverkenning 2, Alphen aan de Rijn, pp 55-65
Williams, R H , Larson, E D , Ross, M H (1987) Materials, Affluence and Industrial Energy Use, Annual Review Energy, 12, p99-144

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1 Such 'optimistic' points of view have in turn been criticized by, for example, Georgescu-Roegen (1971) and Daly (1991) who argue that the ultimate scarce resource is low entropy because of the fixed inflow of solar energy and the finite stocks of concentrated fossil fuels and minerals Substitution is always from one form of low entropy energy matter for another There is no substitute for low entropy itself Since technology is also bounded by the laws of thermodynamics, scarcity is an inescapable aspect of any society that transforms low entropy sources into dissipative high entropy sources

2 Malenbaum has presented his theory not for the absolute consumption of materials but for the relative consumption of materials the amount of materials per unit of income This is the 'intensity of use', which would follow a similar inverted-U curve but with a lower turning point (in Figure 11 1, b would be the turning point of this curve) This has no implications for the elaboration of the theory presented here because Malenbaum acknowledged that further movements along the inverted-U curve would eventually result in absolute reductions of materials consumption

3 See De Bruyn and Opschoor (1997) for an elaboration on how this throughout index has been calculated

4 A similar pattern was found in several other countries that are not given in the figure One may point at the fact that the patterns vary among countries Most countries show relative strong fluctuations in their index between 1973 and 1980 which may reflect the

uncertainty in the resource markets during that period, combined with the nature of the data collected. Since the data exclude changes in stocks, any release or accumulation of stocks of steel, cement or energy will be reflected as consumption in the throughput index During times of uncertainty both governments and speculators may enter the resource market more actively, which may explain the different patterns over time and across countries given in Figure 11 3.

Attractor points not only have an implication for the shape of the consumption of resources over time, they also have a clear econometric equivalence in terms of co-integration. The fact thatshocks permanently shift the equilibrium relationship between resources and income to a new attractor point implies that the consumption of resources and income are not co-integrated The absence of co-integration may imply that most of the estimations proving the intensity of use hypothesis are statistically not supportable (cf Labson and Crompton, 1993)

Review Draft

HYDROGEN PRODUCTION FROM COAL AND COAL BED METHANE, USING BYPRODUCT CO_2 FOR ENHANCED METHANE RECOVERY, WITH CO_2 SEQUESTRATION IN THE COAL BED

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ABSTRACT

Rapid advances being made in proton exchange membrane fuel cell technology for transportation and stationary combined heat and power market applications are creating renewed interest in hydrogen, the preferred fuel for these fuel cells. A promising strategy for providing the needed hydrogen in countries such as China that are coal- and coal-bed-methane-rich but poorly endowed with conventional hydrocarbon resources would be to produce hydrogen from coal and coal bed methane, using the low-cost CO_2 generated as a byproduct of hydrogen production to stimulate the recovery of methane from deep beds of unminable coal—a promising new technique recently advanced for recovering coal bed methane. While awaiting the arrival of fuel cells for major commercial applications, hydrogen so produced might be used in the manufacture of ammonia for fertilizer, as a less costly option for hydrogen manufacture than making it from coal only, which is a common practice in China. Moreover, the production of hydrogen in this manner from coal plus coal bed methane would lead to low levels of lifecycle CO_2 emissions, because the CO_2 injected into the coal bed for methane recovery would remain sequestered there. This strategy stands out as a promising major option for using coal with low local and global environmental impacts.

BACKGROUND

There are substantial activities in the United States, Europe, and Japan aimed at accelerating the commercialization of the proton exchange membrane (PEM) fuel cell (FC) for both stationary distributed combined heat and power (CHP) generation in residential and commercial buildings (as an alternative to central station power generation) (Dunnison and Wilson, 1994; A.D. Little, 1995) and for transportation applications (as an alternative to the internal combustion engine)(Kircher et al., 1994; Mark et al. 1994;Williams, 1993, 1994). For these applications, the PEM FC offers large primary energy savings as a result of energy efficiency gains, zero or near-zero local air pollution without the need for end-of-pipe pollution control technologies, the opportunity to diversify the fuel supplies for the transport sector, and the potential for realizing deep reductions in greenhouse gas emissions without large increases in the costs of energy services. For distributed CHP and transit bus applications, the technology will be commercially available before the year 2000 (Prater, 1996). Car manufacturers in Europe, Japan, and the United States are seeking to develop and commercialize FC cars for the much larger automotive markets, with automobile market entry targeted for the period 2004-2010—see Box A.

If ongoing efforts to commercialize the PEM FC are successful, fossil fuels could play far greater roles in a greenhouse-emissions-constrained world than if only conventional fossil-fuel conversion technologies were available, because:

(*i*) the PEM FC "prefers" to be supplied with hydrogen (H_2) fuel,[1]

(*ii*) their commercialization could spur a shift to an energy economy in which H_2 would be derived primarily from carbonaceous feedstocks[2] and the byproduct CO_2 could be isolated from the atmosphere at low incremental cost,[3] and

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1 All fuel cells use as fuel H_2 that is produced either at the point of use or at a centralized facility and delivered to the user by pipeline or other means. The PEM fuel cell operates at such a low temperature (~ 80 °C) that point-of-use fuel processing of a conventional liquid or gaseous fuel to produce a H_2-rich gas suitable for fuel cell use is relatively inefficient because little if any "waste heat" from the fuel cell is available for fuel processing, in contrast to the situation with high temperature fuel cells (e.g., solid oxide or molten carbonate fuel cells).

2 H_2 is manufactured thermochemically from carbonaceous feedstocks through processes that begin with the production of synthesis gas, a gaseous mixture consisting mainly of CO and H_2. [Synthesis gas can be produced from natural gas by steam reforming or from coal, oil, or municipal solid waste by oxygen-blown gasification or from biomass using indirect gasifiers (Williams et al., 1995a, 1995b)] Next the synthesis gas is reacted with steam ($H_2O_{(g)}$), thereby converting the CO and $H_2O_{(g)}$ into H_2 and CO_2. The H_2 is then readily separated by chemical or physical gas separation techniques from the resulting gaseous mixture that consists mainly of CO_2 and H_2.

H_2 produced in this manner will be far cheaper than H_2 derived electrolytically from water using any electricity source (Williams, 1996; Williams and Wells, 1997), except where off-peak hydroelectric power (for which the capital charge in the electricity price paid by the H_2 producer is zero) is available. (Supplies of off-peak hydroelectric power are adequate for serving only niche markets.) A large cost advantage for thermochemically-derived H_2 holds even when the costs of sequestering the CO_2 separated out at the H_2 production plant are taken into account (Williams, 1996).

3 In producing H_2 from a carbonaceous feedstock, a concentrated stream of CO_2 accounting for most of the carbon in the feedstock can be generated as a byproduct and stored in isolation from the atmosphere with low overall penalties on the H_2 production cost (Williams, 1996; Blok et al., 1997; Williams, 1997).

(*iii*) there are large underground reservoirs in which CO_2 could be securely isolated from the atmosphere.[4]

Although H_2 is the fuel of choice for use with the PEM FC, a H_2 fuel infrastructure is not yet in place. Accordingly, for many applications the PEM FC will be introduced into the market using the existing hydrocarbon (HC) fuel infrastructures, with conversion of the HC fuel into a H_2-rich gas suitable for fuel cell use at the point of use—e.g., onsite reforming of natural gas for CHP applications and liquid HC fuel processing onboard a car (Mitchell et al., 1995), a strategy being pursued by two US automaker (see Box A). These are likely to be only transitional strategies, however, because of the preference of the PEM FC for H_2 fueling. It has been shown, for example, that if the FC car is successfully launched in the market with a liquid HC fuel, the automotive system would generate internal market pressures to shift to H_2 as soon as the H_2 infrastructure could be put into place, as a result of the higher first cost, higher maintenance cost, and lower fuel economy of the gasoline FC car relative to the H_2 FC car (Ogden et al., 1997; Williams, 1997).

Coal-rich countries that have are not well endowed with petroleum resources and that do not yet have extensive HC fuel infrastructures in place (e.g., China) have the opportunity to "leapfrog" directly to H_2 fuel cell technology, obviating the need for the costly HC FC transition technology. Moreover, if PEM FC technology were to be introduced sufficiently quickly in the transport sectors of such countries, they could avoid altogether the need to develop a pervasive liquid HC fuel infrastructure for transportation (Williams, 1998).

The present paper assesses the prospects for H_2 production from coal and methane recovered from deep coal beds, using the byproduct CO_2 for enhanced coal bed methane (CBM) recovery and sequestration of the injected CO_2 in these beds. This strategy seems well suited for beginning a transition to a H_2 FCs in countries such as China that have substantial coal and CBM resources but limited petroleum resources (Williams, 1998). Initially, while awaiting the introduction of FC technology, the H_2 so produced might be used in the manufacture of ammonia for fertilizer.

CBM RESOURCES AND CURRENT CBM RECOVERY TECHNOLOGY

Coal beds are both source rocks and reservoir rocks for large quantities of methane-rich gas. This gas is typically produced at rates ranging from 150 to 200 normal cubic meters (Nm^3)[5] per tonne of coal throughout the burial history of the coal as a result of biogenic and thermogenic processes whereby plant material is progressively converted to coal (Rice et al., 1993). Large amounts of methane produced

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4 There is increasing confidence in the scientific community that the capacity of underground storage reservoirs (depleted oil and gas fields, deep saline aquifers, and deep coal beds) for storing CO_2 securely for long periods of time is very large, suggesting that a fuel cell energy strategy based on the use of fossil fuel-derived H_2 could make feasible major roles for fossil fuels in a severely greenhouse gas emissions-constrained world (see the Appendix).

5 The Nm^3 is evaluated at 0.0101325 MPa (1 atmosphere) and 273.15 K.

Box A: Progress in Developing Motor Vehicles Powered by PEM Fuel Cells

1993	Clinton Administration announces Partnership for a New Generation of Vehicles (PNGV) with U.S. automakers, aimed at introducing by 2004 production-ready prototypes of "cars of the future" that will be three times as fuel efficient as today's cars but will maintain size and performance and cost no more to own and drive
1993	Ballard Power Systems of Vancouver (Canada) introduces proof-of-concept H_2 PEM fuel cell bus (with compressed H_2 storage)
1995	Daimler-Benz introduces NECAR I, a H_2 PEM fuel cell test van (with compressed H_2 storage, Ballard fuel cell)
1995	Ballard demonstrates H_2 PEM fuel cell bus suitable for commercial use (with compressed H_2 storage)
1995	Mazda demonstrates a H_2 PEM fuel cell golf cart (with compressed H_2 storage)
1996	Daimler-Benz introduces NECAR II, a prototype passenger van equipped with a compact H_2–powered fuel cell system (power density of 1 kW_e/liter, 0.7 kW_e/kg for the fuel cell stack) developed jointly with Ballard (with compressed H_2 storage)
1996	Toyota introduces prototype PEM H_2 fuel cell car (with metal hydride storage)
1996-97	Ballard sells several H_2 PEM fuel cell buses to cities of Chicago and Vancouver
1997	Ballard and Daimler-Benz form joint venture with $320 million planned investment to develop PEM fuel cell cars, with commercialization targeted for 2005 timeframe
1997	Daimler-Benz introduces NECAR III, a prototype small fuel cell passenger car [with onboard methanol (MeOH) reformer]
1997	Toyota introduces prototype fuel cell passenger car (with onboard MeOH reformer)
1997	Ford joins Daimler-Benz & Ballard in joint venture to commercialize fuel cell cars, bringing planned pooled investment total to $420 million; fuel cell power trains for cars targeted for commercialization in 2004
1998	GM announces it will develop production-ready prototype fuel cell cars by 2004
1998	Chrysler announces it will develop production-ready prototype fuel cell cars by 2004 (with onboard gasoline partial oxidation systems)
1998	Mobil Corporation and Ford Motor Company form a strategic alliance to develop a hydrocarbon fuel processor for use in fuel cell vehicles

this way will remained trapped in the coal bed, adsorbed on coal surfaces. Because coal is a microporous solid with large internal surface areas (tens to hundreds of square meters of per gram of coal!), it has the ability to adsorb large amounts of gas and can hold up to five times as much gas as a comparable conventional natural gas reservoir of comparable size, at the same temperature and pressure (Gunter et al., 1997). In general, gas content increases with increasing coal rank; typically lignites contain very little gas, while high-rank coals (e.g., medium- or low-volatile bituminous coals, semianthracite, or anthracite) can contain as much as 30 Nm^3/tonne. For medium-volatile or higher ranks, the coals may have generated more methane than they can store, resulting in the expulsion of the excess methane into adjacent reservoirs (e.g., trapped under a caprock above the coal bed). The amount of gas that can be stored in a particular coal as a function of reservoir pressure at a constant temperature is commonly determined from a sorption isotherm (Rice et al., 1993). Figure 1 shows an idealized coal-bed gas sorption isotherm showing the relationship between gas content and reservoir pressure. The heavy solid line indicates the maximum amount of gas that can be stored at a given reservoir pressure—e.g., 17 Nm^3 per tonne (17 cc/gr) of coal at 10 Mpa = 100 bar.[6]

CBM resources are substantial. Worldwide CBM resources are estimated to be 85 to 262 trillion Nm^3 (Rice et al., 1993); the corresponding energy value is 3,400 to 10,400 EJ (assuming the gas is entirely CH_4 with a HHV of 39.72 MJ/Nm^3), equivalent to 0.3 to 0.9 times the mean estimate of remaining recoverable conventional natural gas resources worldwide (Masters et al., 1994). In China, CBM resources are estimated to be 30 to 35 trillion Nm^3 (Rice et al., 1993); the corresponding energy value is 1,190 to 1,390 EJ; for comparison, the mean estimate of the remaining recoverable conventional natural gas resources in the United States is 695 EJ (Masters et al., 1994). The fraction of the CBM resource that can be recovered economically depends on both the quality and accessibility of the resource and the recovery technology employed.

CBM is recovered commercially in the US, mostly in the San Juan Basin of New Mexico and Colorado and the Black Warrior Basin of Alabama and Mississippi (McCabe et al., 1993). U.S. CBM production grew rapidly from about 40 billion standard cubic feet (bscf)[7] (1.1 billion Nm^3) in 1988 to 350 bscf (9.4 billion Nm^3) in 1991 (McCabe et al., 1993) to 950 bscf (25.5 billion Nm^3) in 1996[8] (private communication from Karl Schultz, US EPA, 27 June 1997), when CBM production accounted for about 6% of total US natural gas production, of which only but 30 .

Current practice is to depressurize the coal bed (usually by pumping water out of the reservoir), which leads to desorption of the gas from the micropores of the coal matrix, its diffusion through the coal matrix to macrofractures in the coal called "cleats," and its flow through the cleats to the wellbore for recovery (see Figure 2). The process is simple and effective but slow and inefficient; depressurization deprives the fluids of the energy to flow readily to the wellbore. There is typically a significant time lag (days to months) between the beginning of the dewatering process and the time when substantial gas recovery rates are realized (see Figure 3).

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6 For areas characterized by the average geopressure gradient a hydrostatic pressure of 100 bar is found at a depth of 870 meters.

7 The scf is evaluated at 14.696 psia (0.101352 MPa) and 60 °F (288.56 K). Note that 1 scf = 0.02685 Nm^3

8 Only 30 bscf of the CBM recovered in 1996 (3%) was associated with coal mining operations.

USING CO_2 INJECTION FOR CBM RECOVERY AND THE COAL BED FOR CO_2 SEQUESTRATION

An alternative approach to CBM recovery that holds forth the prospect of being far more efficient is gas injection; for this purpose CO_2 is especially promising because it is twice as adsorbing on coal as CH_4; it can therefore efficiently displace the CH_4 adsorbed on the coal (Gunter et al., 1997). CO_2 injection makes it possible to maintain reservoir pressure and produce CH_4 gas quickly. As CO_2 moves through the reservoir it displaces CH_4; it has been found that very little of the injected CO_2 shows up in the production well until most of the CH_4 has been produced (Gunter et al., 1997). Thus the prospects for permanent sequestration of the injected CO_2 are good. Of course, sequestration of CO_2 in the coal bed would prevent subsequent mining of the coal. However, for much of the coal lying in deep beds that contain substantial quantities of CBM and that would be especially favorable sites for CO_2 sequestration mining the coal would be uneconomical.[9]

Although the recovery of coal bed methane (CBM) via CO_2 injection into deep coal beds is not yet commercial, the technology could be could be commercialized in five years or less if there were sufficient market interest.

The major challenge regarding this approach to CBM recovery is to have available a source of low-cost CO_2 at the prospective CBM recovery site. Such a low cost CO_2 source can be made available in a relatively pure stream as a byproduct of H_2 manufacture from fossil fuels with modern techniques in the amount 29.7 kgC per GJ of H_2 (0.71 kmol CO_2 per kmol H_2) produced from coal and 10.7 kgC per GJ of H_2 (0.25 kmol CO_2 per kmol H_2) produced from methane (Williams, 1996).

China currently makes H_2 through coal gasification in large amounts as an intermediate product in the manufacture of ammonia,[10] largely for the production of fertilizer. Because of the scarcity of its conventional natural gas resources, 70% of China's NH_3 production in 1990 was based on the gasification of some 37 million tonnes of coal (Li et al., 1990). Moreover, China is rapidly building up a

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9 If all the world's estimated 85 to 262 trillion Nm^3 CBM resources could be exploited by CO_2 injection with sequestration of the injected CO_2, the global sequestration potential would be 90 to 280 GtC of CO_2. However, some of these resources will not be suitable for recovery via CO_2 injection, and some will be associated with minable coal resources, for which permanent CO_2 sequestration would probably not be considered.

10 NH_3 is produced via the Haber process by combining (at a pressure in the range 130 to 680 atmospheres) nitrogen (N_2) and H_2 in the presence of an appropriate catalyst, according to:

$$N_2 + 3H_2 \rightarrow 2NH_3.$$

NH_3 can be made from coal, producing the needed H_2 via oxygen-blown coal gasification. Both the oxygen (O_2) needed for coal gasification and the N_2 needed for the Haber process can be obtained by air liquefaction. The oxygen-blown gasifier produces from coal at high efficiency "synthesis gas," a gaseous mixture consisting mainly of carbon monoxide (CO) and H_2. The CO in this synthesis gas is then reacted with steam in so-called "water-gas shift reactors," producing more H_2 plus CO_2. The net effect of gasification and shifting is thus to produce a gaseous mixture consisting mainly of H_2 and CO_2. Various commercial technologies are available for separating the H_2 (with up to 99.999% purity) from the CO_2 in the resulting gaseous mixture. For modern plants the H_2 produced this way would have an energy content (on a higher heating value basis) greater than 60% of the energy content of the coal from which it is derived (Williams et al., 1995a; 1995b).

capacity to make fertilizer from coal using modern coal gasification technology. China already has in operation, under construction, or on order, 25-30 modern, oxygen-blown coal gasifiers, all for applications in the chemical process industries, mostly for ammonia production.[11] Chinese interest in such technology arises both as a result of the expected continuing increase in the demand for nitrogen fertilizer[12] and because much of the existing coal-based NH_3 production is based on the use of small, inefficient, and polluting plants,[13] many of which are likely to be replaced with larger, cleaner, and more cost-competitive plants. The more modern coal gasification technology could also be used to make H_2 for fuel cell applications.

AN OPPORTUNITY FOR LAUNCHING A CBM INDUSTRY IN CHINA USING BYPRODUCT CO_2 AT NH_3 PLANTS

China has a major opportunity to establish a CBM recovery industry based on CO_2 injection by locating new plants for making NH_3 from coal near prospective CBM recovery sites and using the low-cost CO_2 produced as a byproduct of NH_3 production for stimulating the production of CBM.

When NH_3 is manufactured from coal the byproduct CO_2 generation rate amounts to somewhat more than one kmol of CO_2 per kmol of NH_3. The amount of CO_2 potentially available for applications such as CBM recovery depends on the form of the fertilizer produced. If the desired product is ammonium nitrate, all the byproduct CO_2 is available. If instead the desired product is urea, about half the separated CO_2 is needed for urea manufacture.[14] In either case the excess CO_2 could be used for

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[11] More than 20 Texaco gasifiers are operating, under construction, or on order for the production of chemical fertilizer, methanol, town gas, and oxochemicals. In addition, about six Shell gasifiers and at least one Lurgi gasifier are being used to produce ammonia from coal.

[12] The production of NH_3 is projected to increase from 22.5 million tonnes in 1990 to 37.8 million tonnes in 2020 (Li et al., 1995). Fertilizer demand is not expected to grow more rapidly than this because China already uses fertilizer at a high rate—some 148 kg/hectare/year, compared to a world average of 54 kg/hectare/year.

[13] In 1990 18.7% of total NH_3 production in China was accounted for by large, relatively efficient plants that use natural gas or oil as feedstocks; most of the rest of the ammonia production was accounted for by much less efficient medium-scale and small-scale plants that use coal (Li et al., 1995).

[14] When NH_3 is used as a feedstock to produce urea for fertilizer, first CO_2 is reacted with NH_3 to form ammonium carbamate:

$$NH_3 + \tfrac{1}{2}\, CO_2 \rightarrow \tfrac{1}{2}\, NH_4COONH_2,$$

and then the ammonium carbamate is dehydrated to form urea (NH_2CONH_2):

$$NH_4COONH_2 \rightarrow NH_2CONH_2 + H_2O.$$

Because only about half of the available CO_2 is needed for the production of urea, the excess CO_2 could be used to stimulate CBM recovery from deep coal beds as an alternative to venting this CO_2 to the atmosphere, as is typically done today at urea plants.

stimulating CH_4 recovery from deep beds of unminable coal, if such beds were located nearby..

In what follows the results of a study modeling systems of CBM recovery and use constructed in connection with the manufacture of NH_3 from coal are described. It is assumed that NH_3 manufacturing plants are located near sites with deep unminable coal deposits containing CBM. It is also assumed that the CBM resource characteristics are similar to those in CBM-rich areas of the San Juan Basin in the United States (Kuuskraa and Boyer, 1993).

For all cases, CBM recovery and use are considered in conjunction with the manufacture of 25.8 PJ (2.0 billion Nm^3) per year of H_2 from coal for fertilizer applications (ammonium nitrate in Cases Ia and IIa and urea in Cases Ib and IIb). It is assumed that the CBM resource is recovered over a 25-year period, the assumed lifetimes for the H_2 production plants.

Two alternative uses of the recovered CBM are considered:

(i) *Case I*, for the production of additional H_2 feedstock for making more NH_3 and also providing more byproduct CO_2 for stimulating more CBM recovery [Case Ia for ammonium nitrate (NH_4NO_3) production (see Figures 4 and 5 and Table 1) and Case Ib for urea production (see Figure 6 and Table 1)], and

(ii) *Case II*, for the production of electricity in a gas turbine/steam turbine combined cycle power plant [in conjunction with NH_4NO_3 production from coal in Case IIa (see Figure 7 and Table 2) and in conjunction with urea production from coal in Case IIb (see Table 2)].

In both instances production rates, costs, and CO_2 emission rates are compared to *Base Cases*, in which H_2 and electricity are produced from coal only with venting to the atmosphere of the CO_2 produced in H_2 manufacture that is not used for urea manufacture (see Tables 1 and 2).

The systems described have scales that are consistent with modern coal production systems. For example, the largest CO_2 injection rate considered (Case Ia)[15] is 460 tonnes of CO_2/hour in Case Ia This is approximately the CO_2 generation rate for a 500 MW_e coal steam-electric power plant. This case also involves the highest CBM production rate, some 37 PJ (920 million Nm^3) per year.

The CBM cost estimates presented here (see Table 4 for Case Ia) are in two parts:

i) *CBM recovery cost estimates* by Kuuskraa and Boyer (1993) for conventional CBM recovery techniques, less the Kuuskraa/Boyer estimates of the costs for conventional (hydraulic) methods of stimulating CBM recovery, applied to CBM reservoirs similar to those in the CBM-rich parts of the San Juan Basin, plus

ii) *costs for stimulating CBM recovery with CO_2 injection* [costs for CO_2 compression, transport, and injection, based on previous analyses relating to CO_2 sequestration in depleted natural gas fields (Blok et al, 1997) and aquifers (Hendriks, 1994), modified as appropriate to reflect assumed coal bed reservoir characteristics].

The smallest CO_2 injection rate considered (Case IIb) is 181 tonnes of CO_2/hour.

Because the use of CO_2 injection for CBM recovery is not yet commercial technology, and because costs will be very site specific [depending on the reservoir geometry, permeability (a measure of the ability of a gas to flow through the reservoir as a result of the structure and interconnection of the pore spaces), the placement and distribution of CO_2 injection wells and CBM recovery wells, etc.], the cost estimates presented here are very preliminary. However, because no increase in system productivity is assumed for CBM recovery with CO_2 injection compared to the use of conventional CBM recovery technology, the cost estimates presented here may well be overestimates.[16]

The energy and mass balances for CBM production in Case Ia are presented in Table 3 and estimated CBM recovery costs for this case are presented in Table 4. The corresponding energy and mass balances and the costs for H_2 production from CBM in this case are presented in Tables 4 and 5, respectively, along with the same parameters for Base Case H_2 production from coal. In this case, it is assumed that the CBM is recovered from an array of 200 wells[17] in a circular field having an area of 130 km^2 (so that the recovery field area per CBM recovery well is 65 hectares), at the center of which the energy conversion facility is located. It is assumed that the wells are arranged such that aggregate output of all the wells can be maintained at a relatively constant level over the assumed 25-year life of the CBM recovery facility. With 200 wells the average CBM recovery rate is 12,700 Nm^3 (0.47 million scf) per day per well,[18] so that the ultimate recovery is 1.78 million Nm^3 (66 million scf) per hectare.[19] It is assumed that the average well depth is 856 m [the average for all CBM wells drilled in the United States in 1990 (Petzet, 1991)], and that CBM well costs are the same as the average for all CBM wells drilled in the United States in 1990, some $291 per m (Petzet, 1991). Costs for CBM recovery per well other than for the recovery wells are assumed to be the same as costs estimated by Kuuskraa and Boyer (1993), except that hydraulic "well stimulation costs" as estimated by those authors are replaced here by costs for CO_2 compression, transport, and injection into the coal bed.

It is assumed that the CO_2 recovered at the H_2 production plants at 1.3 bar is compressed to 100 bar and transported by pipeline to the CO_2 injection sites. The CO_2 injection rate for a well (which determines the number and spacing of wells) is directly related to the reservoir thickness, its permeability, and the difference between the pressure at the bottom of the well and the reservoir pressure at a large distance from the well. For simplicity (and in the absence of any specific data for CBM reservoirs in China) it is assumed that the reservoir is a uniform, horizontal, 10-m thick coal bed,[20] that

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16 In the CBM recovery cases discussed by Gunter et al. (1997) cumulative CBM recovery is enhanced by more than a factor of two with CO_2 injection and the CBM is produced much earlier with CO_2 injection compared to primary pressure depletion methods.

17 The number of CBM wells is assumed to be proportional to the rate of CO_2 injection. Accordingly, there are 79, 154, and 82 CBM recovery wells for Cases Ib, IIa, and IIb, respectively.

18 For comparison, at the end of 1991 there were 1660 CBM wells in the San Juan Basin producing CBM at an average rate of 0.60 million scf per day per well (Kuuskraa and Boyer, 1993).

19 In the CBM-rich regions of the San Juan Basin the CBM resource in place is in the range 2 to 4 million Nm^3 per hectare (Kuuskraa and Boyer, 1993).

20 In the CBM-rich Fruitland Formation of the San Juan Basin coal bed thickness range between 6 and 24 m

the coal bed permeability is 10 millidarcies,[21] and that the pressure difference between the well-bottom and the reservoir is 80 bar.[22] Under these conditions, the CO_2 injection rate per well would be about 28 tonnes of CO_2 per hour,[23] so that about 16 wells would be needed for Case Ia (i.e., there would be on average 12.5 CBM recovery wells per CO_2 injection well).

Results of the Case I analyses are presented in Table 1. In Case Ia the amount of H_2 derivable from CBM is 82% of what is produced in the Base Case; in Case Ib the amount of H_2 derivable from CBM is 17% of what is produced in the Base Case. The net lifecycle CO_2 emissions for CBM-derived H_2 are negative because all the costs for CO_2 injection and thus credit for the CO_2 sequestered are assigned to CBM production and thereby to the manufacture of H_2 from CBM. Emissions of CO_2 per GJ associated with H_2 manufacture from coal are also 1/3 less than in the Base Cases, because with CO_2 injection CBM (the use of which is characterized by negative net lifecycle CO_2 emissions) rather than coal is used to provide the external electricity (in a 45%-efficient[24] combined cycle) and heat (in an 85%-efficient boiler) needed to make H_2 from coal. The average net emission rate for the entire system of H_2 production from coal plus CBM is 6.0 kgC/GJ$_{H2}$ (15% of the emission rate for H_2 production in

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(Kuuskraa and Boyer, 1993).

21 A typical value for coal beds (Gunter et al., 1997). One millidarcie = 10^{-15} m^2.

22 The pressure at the well bottom is 99.5 bar (pressure at the wellhead) + (0.092 bar/m)*d, where d = well depth in meters (Hendriks, 1994) For the assumed value of d = 856 m, the pressure at the well bottom is 178 bar. Assuming a normal hydrostatic geopressure gradient of 115 bar per km, the reservoir pressure at 856 m is 98 bar. Thus the pressure difference is 80 bar.

23 The feasible CO_2 injection rate per well (and thus the number of injection wells needed) depends directly on the thickness of the coal bed and its permeability to the flow of CO_2. These parameters can be related by the following heuristic formula used by reservoir engineers (Hendriks, 1994):

$$q_s = 2\pi (\rho_r/\rho_s) kh \Delta P/[\mu \ln (r_e/r_w)],$$

where:

q_s = CO_2 flow rate [Nm^3/s],
ρ_r = CO_2 density under coal bed conditions = 700 kg/m^3 (typical value for supercritical CO_2),
ρ_s = CO_2 density under standard conditions = 1.97 kg/Nm^3,
k = permeability of the coal bed [m^2],
h = thickness of coal bed [m],
ΔP = difference between CO_2 pressures at the well bottom and at a long distance from the well [Pa],
μ = viscosity of the CO_2 at the well bottom = 6 x 10^{-5} Pa s (typical value),
r_e = radius of the influence sphere of the injection well [m],
r_w = radius of the injection well [m].

It is assumed that h = 10 m (see footnote 20), that k = 10^{-14} m^2 (10 millidarcies) (see footnote 21), and that ΔP = 80 bar = 8,000,000 Pa (see footnote 22). Following Hendriks (1994), it is assumed that $\ln (r_e/r_w)$ = 7.5. Thus the CO flow rate assumed per well in the present analysis is q_s = 3.97 Nm^3/s = 28.2 tonnes/h.

24 All efficiencies presented in this paper are based on higher heating values (HHVs) for fuels.

the Base Case) for Case Ia and 19.0 kgC/GJ_{H2} (50% of the emission rate in the Base Case)for Case Ib.

Results of the Case II analyses are presented in Table 2. CBM production is adequate to support 50%-efficient combined cycles at scales of 485 MW_e and 248 MW_e in Cases IIa and IIb, respectively. The amount of electric generating capacity in excess of onsite needs (both for H_2 production from coal and for CBM recovery) that can be supported by the recovered CBM amounts to 336 MW_e in Case IIa and 120 MW_e in Case IIb. As in the case of CBM-derived H_2, the net lifecycle CO_2 emissions for CBM-derived electricity are negative; emissions of CO_2 associated with H_2 production from coal are also 1/3 less than in the Base Cases. The average net emission rate for the entire system of H_2 production from coal plus electricity production from CBM are, for Case IIa ¼ as much, and, for Case IIb ½ as much, as in the Base Cases (defined as producing from coal without CO_2 sequestration the same .amounts of H_2 and electricity as in Cases IIa and IIb).

In all cases considered here the estimated CBM production cost is in the range $1.7 to $1.8 per GJ.[25] If these cost estimates prove to be reasonably good, CBM will come to be viewed as a very competitive[26] as well as a very clean energy source. At such CBM prices the estimated cost of the extra H_2 produced from CBM in Case Ia is about $4.2/$GJ_{H2}$, some 60% of the cost of H_2 produced from $1.0/GJ coal in the Base Case (see Table 6); in Case Ib the cost of CBM-derived H_2 is $5.2/$GJ_{H2}$, about 70% of the cost of H_2 in the Base Case.

For Cases IIa and IIb the estimated cost per kWh of the electricity produced in CBM-fired combined cycle plants is about 80% of the cost of producing electricity from $1.0/GJ coal in steam-electric power plants in the Base Cases. Moreover, local air pollutant emissions would be much less, in light of the fact that electricity generated from natural gas in combined cycle power plants has the lowest local air pollutant emissions of all fossil fuel thermal-electric power generating technologies.

Cases I and II require comparable financial investments beyond the coal-related investments required (e.g., $387 million for Case Ia[27] and $438 million for Case IIa[28]). The total capital at risk, however, is greater for Case I than for Case II. In Case I, some of the extra capital equipment for making NH_3 out of the CBM-derived H_2 would be idled at high cost if there were substantial unexpected reductions in the CBM recovery rate. But in Case II, where much of the produced electricity is exported to the utility grid [70% of the electricity produced in Case IIa (see Figure 7) and 50% in Case IIb], unexpected shortfalls in CBM recovery could probably be readily compensated for by other underutilized electric generating capacity on the electric utility grid, so that the financial risks associated with the uncertainty in the CBM recovery rate would be much less; moreover, in Case IIa, CBM electricity would still be competitive with coal electricity if the combined cycle power plant capacity factor were reduced from the assumed 90% to about 50% (with the capacity factor of the coal plant fixed at 90%). Thus

25 Cost estimates and prices in this paper are in 1991 U.S. dollars.

26 For comparison, the average U.S. wellhead natural gas price (in 1991$) in 1996 was $1.80/GJ (EIA, 1997)

27 $152 million for CO_2 compression, transport, and injection; $155 million for CBM recovery; and $80 million for the combined cycle plant. See Table 4.

28 $118 million for CO_2-related activities, $120 million for CBM recovery; and $200 million for the combined cycle plant.

initially, until the technology of CBM recovery is well enough understood that there can be a high degree of confidence that steady CBM recovery rates can be sustained, Case II strategies might be favored over Case I strategies for utilizing the recovered CBM.

Once the technology for using CO_2 injection for stimulating CBM recovery is well established, the use of the CBM for the production of additional H_2 (Case I) should be considered wherever there is a sufficiently high market for H_2 (e.g., for extra NH_3 production in the near term or for fuel cell applications in the longer term), in light of the much lower cost of making H_2 from CBM than from coal. When the major market for the produced H_2 is fuel cells, the energy/material balances and costs will be very similar to those for Case Ia rather than Case Ib, since in this instance all the byproduct CO_2 can be injected into the coal bed for stimulating CBM recovery and CO_2 sequestration.

This analyses indicates not only that there are likely to be large local and global environmental benefits associated with CO_2-stimulated CBM recovery carried out in conjunction with the production of H_2 for ammonia manufacture from coal in China, but also that there are favorable prospects that CBM production carried out in this manner would be economically competitive in serving near-term H_2 or electricity needs. These findings highlight the importance of developing this CBM recovery technology quickly.

THE POTENTIAL FOR HYDROGEN DERIVED FROM COAL AND CBM FOR TRANSPORTATION APPLICATIONS IN CHINA

If fuel cells were to become well established in transportation markets in China, H_2 derived from coal plus CBM in the manner described above for NH_3 manufacture could play major roles in fueling fuel cell vehicles in China's transportation system. This point is illustrated by a *gedanken* experiment presented in a companion paper (Williams, 1998). In this experiment H_2 is so produced in quantities adequate to support a hypothetical future automotive fleet of 350 million H_2 fuel cell cars that have a fuel use rate of 2.35 liters/100 km of gasoline equivalent (100 mpg)[29] and are driven 15,000 km (9300 miles) per year. There it is shown that for such a fleet:

(*i*) the fuel cost per km for typical fuel cell car owners in China would probably not be greater than for owners of gasoline internal combustion engine cars of comparable size and performance;

(*ii*) the coal requirements for supporting such a fleet would be only 13% of total coal use in China in 1990;

(*iii*) a fleet of this size could be supported for 100 years with just ¼ of China's estimated CBM resources; and

(*iv*) the lifecycle CO_2 emissions for H_2 production and use in this system (including the assumed use of coal-derived electricity to operate H_2 compressors at car refueling stations) would amount to

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[29] A fuel use rate of 2.35 liter/100 km (gasoline-equivalent) is typical of expected performance of H_2 fuel cell cars that have acceleration, hill climbing ability, rolling resistance, aerodynamic drag, and weight characteristics that are similar to those for the "car of the future" being developed under the Partnership for a New Generation of Vehicles (Ogden et al., 1997), a joint undertaking involving the U.S. federal government and the "Big Three" automakers in the United States.

only 6% of China's CO_2 emissions in 1990.

And of course the local air pollutant emissions of such a vehicle fleet would be zero.

This *gedanken* experiment shows that indeed H_2 derived from coal plus CBM could play major roles in China's transportation futures without running up against resource or emissions constraints. Although emphasis on passenger transport modes such as buses and two- and three-wheeled vehicles might be preferred alternatives to an automobile-intensive culture in a country with a high population density such as China, such alternatives should be preferred because they would cause less congestion and noise or because adoption of the automobile culture would require sacrificing other development goals, not because of concerns about energy resource constraints—or concerns about local air pollution or greenhouse gas emissions.

CONCLUSION

The recovery of CBM from deep beds of unminable coal by using CO_2 injection into the coal bed to stimulate production appears to be a more promising technique than the conventional method of CBM recovery by reservoir depressurization, if low-cost supplies of CO_2 are readily available. A major ancillary benefit of this strategy is the potential for sequestering substantial quantities of CO_2 in the coal bed, since about 2 carbon atoms will remain as CO_2 adsorbed on the coal for each atom of carbon recovered as methane desorbed from the coal.

Low-cost CO_2 supplies could be provided by locating at prospective sites for CBM recovery facilities for the production from H_2 from fossil fuels, using the byproduct CO_2 for stimulating CBM recovery. N Future demand for H_2 and thus low-cost byproduct CO_2 supplies could be large if PEM fuel cells are successfully commercialized for transportation and stationary CHP markets, as now seems likely.

In countries such as China where conventional oil and natural gas resources are scarce but coal and CBM resources are abundant a near-term opportunity for using this technique for CBM recovery would be to site future plants for making NH_3 from coal near deep CBM reservoirs. The CBM so recovered could be used either to produce more H_2 for NH_3 manufacture or to make electricity in combined cycle power plants. In either case the CBM-derived product (H_2 or electricity) would probably be less costly than the corresponding coal-derived product. This same H_2 production strategy could be pursued later at large scales for energy purposes if PEM fuel cells are successfully established in the market. China's CBM resources so exploited along with coal in the production of H_2 appear to be adequate to support high levels of transportation energy services based on the use of fuel cell vehicles. Moreover, because the CO_2 injected into coal beds to stimulate CBM recovery would remain sequestered there, these coal/CBM-supported transportation services could be provided with very low lifecycle CO_2 emissions.

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APPENDIX: OPTIONS FOR CO_2 STORAGE

Although disposal in the deep oceans is the most-discussed option for CO_2 disposal,[30] much more research is needed to better understand the security of various ocean disposal schemes and their environmental impacts (Turkenburg, 1992). In recent years increasing attention has been given to geological (underground) storage of CO_2: in depleted oil and natural gas fields (including storage in conjunction with enhanced oil and gas recovery), in deep saline aquifers, and in deep coal beds [in conjunction with coal bed methane (CBM) recovery].

Sequestration in depleted oil and gas fields is generally thought to be a secure option if the original reservoir pressure is not exceeded (van der Burgt et al., 1992; Summerfield et al., 1993). One estimate of the prospective sequestering capacity of oil and gas reservoirs associated with past production plus proven reserves plus estimated undiscovered conventional resources (most of which will be used up during the next century) is about 100 GtC for oil fields and about 400 GtC for natural gas fields (Hendriks, 1994); other estimates of the oil and gas field sequestering capacity are as low as 40 GtC for depleted oil fields plus 20 GtC associated with enhanced oil recovery plus 90 GtC for depleted natural gas fields (IPCC, 1996). (For comparison, global CO_2 emissions from fossil fuel burning totaled 6.0 GtC in 1990.) There is a considerable range of uncertainty in the global sequestering capacity of depleted oil and gas fields and the security of such sequestration. More research and field testing are needed to refine sequestering capacity estimates for depleted oil and gas fields, because reservoir properties vary greatly in their suitability for storage, and because the recovery of oil and gas from these reservoirs may have altered the formations and affected reservoir integrity. Although much of the prospective sequestering capacity will not be available until these fields are nearly depleted of oil and gas, CO_2 injection for enhanced oil recovery, which is established technology (Blunt et al., 1993), might become one focus of initial efforts to sequester in profitable ways CO_2 recovered in H_2 production.

Without the benefit of enhanced resource recovery, storage in aquifers will generally be more costly than storage in depleted oil or gas fields. However, deep saline aquifers are much more widely available than oil or gas fields; such aquifers underlie most sedimentary basins, which account for nearly half of the land area of the inhabited continents. To achieve high storage densities, CO_2 should be stored at supercritical pressures (i.e., at pressures in excess of 74 bar). Since the normal hydrostatic geopressure gradient is about 100 bar per km, typically depths of about 800 m or more are required for CO_2 sequestration in aquifers. The aquifers at such depths are typically saline and not connected to the much shallower (typically < 300 m) "sweetwater" aquifers used by people.

If aquifer storage is limited to closed aquifers with structural traps, the potential global sequestering capacity is relatively limited, some 50 GtC (Hendriks, 1994), equivalent to less than 10 years of global CO_2 production from fossil fuel burning at the current rate. However, if structural traps are not required for secure storage, the storage capacity of aquifers would be huge–some 14,000 GtC

30 The deep oceans represent a very large potential sink for anthropogenic CO_2. The ultimate sequestering capacity of the oceans (determined by choosing a nominal allowable change in the average acidity of all ocean water) has been estimated to the in the range 1,000 to 10,000 GtC, the equivalent of 200 to 2,000 years of emissions from fossil fuels (Socolow, 1997). If the injected CO_2 can be incorporated in the general oceanic deep water circulation, a residence time of up to 1,000 years can be anticipated.

(Hendriks, 1994), equivalent to more than 2,000 years of CO_2 emissions from fossil fuel burning at the current global rate. A growing body of knowledge indicates that many large horizontal open aquifers might also provide secure storage if the CO_2 is injected far from the reservoir boundaries (Holloway, 1996). The notion that large horizontal aquifers can provide secure sequestration is a relatively new idea that has led to an increase in confidence that long-term sequestration of a significant fraction of the next several centuries of global CO_2 production from human activities may be feasible (Socolow, 1997; PCAST Energy R&D Panel, 1997).

Good estimates of the aquifer sequestration potential require considerable data gathering for and detailed modeling of specific aquifers. A recent major study carried out under the Joule II Non-Nuclear Energy Research Programme of the European Commission (Holloway, 1996) did a considerable amount of such modeling in an assessment of underground CO_2 storage reservoirs in Europe. This study estimated that the underground storage capacity accessible to the European Union plus Norway (mostly deep aquifers under the North Sea) would be adequate to store more than 200 GtC—storage capacity equivalent to 250 years of CO_2 emissions from all of OECD Europe at the current emission rate.

Experience with aquifer disposal will be provided by two projects involving injection into nearby aquifers of CO_2 separated from natural gas recovered from CO_2-rich gas reservoirs. One is a Statoil project begun in 1996 to recover 1 million tonnes of CO_2 per year from the Sleipner Vest offshore natural gas field in Norway (Kaarstad, 1992). The second, which will commence in about a decade, will involve the recovery of over 100 million tonnes per year (equivalent to about 0.5 percent of total global emissions from fossil fuel burning) from the Natuna natural gas field in the South China Sea (71% of the reservoir gas is CO_2) (IEA, 1996).

CO_2 sequestration in conjunction with CBM recovery is discussed in the main text of this paper

REFERENCES

Blok, K., R.H. Williams, R.E. Katofsky, and C.A. Hendriks, 1997: Hydrogen production from natural gas, sequestration of recovered CO_2 in depleted gas wells and enhanced natural gas recovery. *Energy*, 22 (2-3), 161-168.

Blunt, M., F.J. Fayers, and F.M. Orr, Jr., 1993: Carbon dioxide in enhanced oil recovery. *Energy Conversion and Management*, **34** (9-11), 1197-1204.

Campbell, C.J., and J.H. Laherrere, 1998: The end of cheap oil. *Scientific American*, **278** (3), 78-83, March.

Dunnison, D.S., and J. Wilson: 1994: PEM fuel cells: a commercial reality. In: *A Collection of Technical Papers: Part 3, 29th Intersociety Energy Conversion Engineering Conference*. Monterey, CA, August 7-11, 1260-1263.

EIA (Energy Information Administration), 1997: *Annual Energy Outlook 1998, with Projections Through 2020*, DOE/EIA-0383(98), U.S. Department of Energy, Washington, DC, December.

Gunter, W.D., T. Gentzix, B.A. Rottenfusser, and R.J.H. Richardson, 1997: Deep coalbed methane in Alberta, Canada: a fuel resource with the potential of zero greenhouse emissions. *Energy Convers. Mgmt.*, **38** (Suppl.), pp. S217-S222.

Hendriks, C.A., 1994: *Carbon Dioxide Removal from Coal-Fired Power Plants*. Ph. D. thesis, Department of Science, Technology, and Society, Utrecht University, Utrecht, The Netherlands.

Holloway, S. (British Geological Survey), ed., 1996: *The Underground Storage of Carbon Dioxide*. Report prepared for the Joule II Programme (DG XII) of the Commission of the European Communities, Contract No. JOU2 CT92-0031, Brussels, February.

IEA (International Energy Agency), 1996: CO_2 capture and storage in the Natuna NG project. *Greenhouse Issues*, **22**, 1.

IPCC (Intergovernmental Panel on Climate Change), 1996: Chapter 19: Energy supply options. In: *Climate Change 1995_Impacts, Adaptations, and Mitigation of Climate Change: Scientific-Technical Analyses*. [Watson, R.T., M.C. Zinyowera, and R.H. Moss (eds.)]. Cambridge University Press, Cambridge and New York.

Kaarstad, O., 1992: Emission-free fossil energy from Norway. *Energy Convers. Mgmt*, **33** (5-8), 781-786.

Kassler, P., 1994: *Energy for Development*. Shell Selected Paper, Shell International Petroleum Company, London, England, November, 11 pp.

Kircher, R., S. Birkle, C. Noelscher, and H. Voigt, 1994: PEM fuel cells for traction: system technology aspects and potential benefits. Paper presented at Symposium on Fuel Cells for

Traction Applications Royal Swedish Academy of Engineering Sciences, Stockholm, Sweden, 8 February.

Kuuskraa, V.A., and C.M. Boyer, II, 1993: "Economic and Parametric Analysis of Coalbed Methane," Chapter 17, pp. 373-394, in *Hydrocarbon from Coal, AAPG Studies in Geology No. 38*, American Association of Petroleum Geologists.

Little, A.D., 1995: *Fuel Cells for Building Cogeneration Application_Cost/Performance Requirements and Markets*. Final Report prepared for the Building Equipment Division, Office of Building Technology, U.S. Department of Energy, NTIS, Springfield, VA.

Mark, J., J.M. Ohi, and D.V. Hudson, 1994: Fuel savings and emissions reductions from light duty fuel-cell vehicles. In: *A Collection of Technical Papers: Part 3, 29th Intersociety Energy Conversion Engineering Conference*. Monterey, CA, 7–11 August, pp. 1425–1429.

Masters, C.D., E.D. Attanasi, and D.H. Root, 1994: World petroleum assessment and analysis. *Proceedings of the 14th World Petroleum Congress*. Stavanger, Norway.

McCabe, P.J., D.L. Gautier, M.D. Lewan, and C. Turner, 1993: *The Future of Energy Gases*. U.S. Geological Survey Circular 1115, United States Government Printing Office, Washington, D.C.

Mitchell, W.L., J.H.J. Thijssen, J.M. Bentley, and N.J. Marek, 1995: Development of a catalytic partial oxidation ethanol reformer for fuel cell applications. *Proceedings of the 1995 SAE Alternative Fuels Conference*. SAE Technical Paper Series 952761, pp. 209-217.

Ogden, J., M. Steinbugler, and T. Kreutz, 1997: Hydrogen as a fuel for fuel cell vehicles: a technical and economic comparison. Presented at the 8th Annual Conference of the National Hydrogen Association, Arlington, VA, 11-13 March.

PCAST Energy R&D Panel, 1997. Federal Energy Research and Development for the Challenges of the Twenty-First Century. Report of the Energy Research and Development Panel of the President's Committee of Advisors on Science and Technology (PCAST), November. Available at http://www.whitehouse.gov/WH/EOP/OSTP/html/OSTP_Home.html on the World Wide Web.

Petzet, G.A., 1991: "JAS Pinpoints Cost of Drilling U.S. Wells," *Oil & Gas Journal*, p. 30, 30 December.

Prater, K., 1996: Solid polymer fuel cells for transport and stationary applications. *Journal of Power Sources*, **61**, 105-109.

Rice, D.D., B.E. Law, and J.L. Clayton, 1993: Coal-bed gas—an undeveloped resource. In *The Future of Energy Gases*. U.S. Geological Survey Professional Paper No. 1570. United States Government Printing Office, Washington, DC, pp. 389-404.

Shell International Petroleum Company, 1995: *The Evolution of the World's Energy System 1860-2060*. Shell Centre, London, December.

Socolow, R.H., ed., 1997: *Fuels Decarbonization and Carbon Sequestration. Report of a Workshop by the Members of the Report Committee*. PU/CEES Report No. 302, Center for Energy and Environmental Studies, Princeton University, Princeton, NJ, September. This report is available on the World Wide Web at http://www.princeton.edu/~ceesdoe

Summerfield, I.R., S.H. Goldhorpe [British Coal Corporation, Coal Research Establishment], N. Williams, and A. Sheikh [Bechtel, Ltd], 1993: Costs of CO_2 disposal options. Paper presented at IEA Carbon Dioxide Disposal Symposium, Christchurch College, Oxford, England, 29-31 March.

Todd, D.M., and H. Stoll, 1997: Integrated gasification combined cycle–the preferred power technology for a variety of applications. Paper presented at Power-Gen Europe '97, Madrid, Spain, June.

Turkenburg, W.C., 1992: CO_2 removal: some conclusions. In: *Proceedings of the First International Conference on Carbon Dioxide Removal*. [Blok, K., W. Turkenburg, C. Hendriks, and M. Steinberg, (eds.)]. *Energy Conversion and Management*, **33** (5-8). 819-823. Pergamon Press, Oxford.

van der Burgt, M.J., J. Cantle, and V.K. Boutkan, 1992: Carbon dioxide disposal from coal-based IGCCs in depleted gas fields. In: *Proceedings of the First International Conference on Carbon Dioxide Removal* [Blok, K., W. Turkenburg, C. Hendriks, and M. Steinberg, (eds.)]. *Energy Conversion and Management*, **33** (5-8), 603-610. Pergamon Press, Oxford.

Williams, R.H. 1993: Fuel cells, their fuels, and the U.S. automobile. In: *Proceedings of the First Annual World Car 2001 Conference*, University of California at Riverside, Riverside, CA.

Williams, R.H., 1994: Fuel cell vehicles: the clean machine. *Technology Review*, April, 21-30.

Williams, R.H., 1996: *Fuel Decarbonization for Fuel Cell Applications and Sequestration of the Separated CO_2*. PU/CEES Report No. 295, Center for Energy and Environmental Studies, Princeton University, Princeton, NJ.

Williams, R.H., 1997: Successful commercialization of fuel cell cars as a driver for H_2 infrastructure development Paper prepared for the Workshop on Technological Opportunities for Fuels Decarbonization and Carbon Sequestration, Washington, D.C., July.

Williams, R.H., 1998: Fuel cells, coal, and China. Paper presented at the 9th Annual U.S. Hydrogen Meeting. Implementing a Global Energy Solution, National Hydrogen Association, Washington, DC, 4 March

Williams, R.H., E.D. Larson, R.E. Katofsky, and J. Chen, 1995a: *Methanol and Hydrogen from Biomass for Transportation, with Comparisons to Methanol and Hydrogen from Natural Gas and Coal*. PU/CEES Report No. 292, Center for Energy and Environmental Studies, Princeton University, Princeton, NJ, July

Williams, R.H., E.D. Larson, R.E. Katofsky, and J. Chen, 1995b: Methanol and hydrogen from biomass for transportation. *Energy for Sustainable Development*, **1** (5), 18-34

Table 1. Alternative Schemes for Producing H_2 for Fertilizer Manufacture in Coal-Rich Countries

	Base Cases: H_2 from Coal for Fertilizer Manufacture (Base Cases)[a]		*Case Ia*: H_2 from Coal + CBM for NH_4NO_3 Manufacture (CBM Produced by Injecting into Deep Coal Beds CO_2 Generated in Making H_2)[b]			*Case Ib*: H_2 from Coal + CBM for Urea Manufacture (CBM Produced by Injecting into Deep Coal Beds CO_2 Generated in Making H_2)[b]		
	NH_4NO_3 Production	Urea Production	H_2 from Coal	H_2 from CBM	H_2 from Coal + CBM	H_2 from Coal	H_2 from CBM	H_2 from Coal + CBM
Coal consumption rate (PJ/y)	42.83		33.28	-	33.28	33.28	-	33.28
CBM consumption rate (PJ/y)	-		8.43	28.30	36.73	8.43	6.00	14.43
H_2 production rate (PJ/y)	25.76		25.76	21.12	46.88	25.76	4.48	30.24
CO_2 available (kgC/GJ)	29.70	15.69	29.70	10.69	21.14	15.69	- 3.32	12.87
Use of available CO_2?	Vented to Atmosphere		Injected into Deep Coal Beds to Stimulate Production of CBM					
Coal price ($/GJ)	1.0							
CBM production rate (PJ/y)	-		36.73			14.43		
CBM production cost ($/GJ)[c]	-		1.80			1.72		
H_2 production cost ($/GJ)[d]	7.34		7.23	4.24	5.88	7.20	5.20	6.90
CO_2 emission rate (kgC/GJ)[e]	38.62		25.62	- 17.97	5.98	25.62	- 17.97	19.16

[a] In the Base Cases coal is used both as a feedstock and for providing external electricity (@ 35.5% efficiency) and heat requirements (@ 80% efficiency) in the manufacture of H_2.

[b] In these cases (Case Ia is shown in Figures 4 and 5) 85%-efficient CBM boilers are used to provide the external heat and 45%-efficient CBM-fired combined cycles are used to provide the external electricity required in H_2 manufacture from both coal and CBM, and coal is used only as a feedstock in the manufacture of H_2 from coal.

[c] The CBM production cost is developed in Table 4 for Case Ia, where CO_2 generated in making H_2 from coal is injected into the coal bed at a rate of 29.70 kgC/GJ_{H2} (NH_4NO_3 fertilizer production case) and the CBM production rate is 36.73 PJ/y; the same procedure is followed for Case Ib.

[d] The costs for producing H_2 pressurized to 300 bar from coal only (Base Case) and from CBM for Case Ia (where the H_2 is used to make NH_4NO_3 fertilizer) are developed in Table 6. The cost of producing H_2 from CBM is much higher for the urea production case because of the scale economy effect at the lower CBM-derived H_2 production rate (4.48 PJ/y vs. 21.12 PJ/y), which arises because with urea production far less CO_2 is available for injection into the coal bed and thus far less CBM can be recovered and converted to H_2.

[e] The CO_2 emissions rates for burning coal and CBM are 23.23 kgC/GJ_{coal} and 13.57 kgC/GJ_{CBM}, respectively. However, because costs associated with CO_2 sequestration are allocated to the cost of CBM production, credit for the CO_2 sequestered in the deep coal bed is assigned to CBM consumption at a rate of 26.98 kgC/GJ, so that the net emissions associated with CBM consumption 13.57 - 26.98 = - 13.41 kgC/GJ_{CBM}.

Table 2. Alternative Schemes for Producing Electricity In Conjunction with the Manufacture of Fertilizer from Coal-Derived H_2

	Base Cases: H_2 from Coal for Fertilizer Manufacture + Coal Steam-Electric Power[a]		*Case IIa*. H_2 from Coal for NH_4NO_3 Manufacture + CC CBM Power (CBM Produced by Injecting into Deep Coal Beds CO_2 Generated in Making H_2)[a]	*Case IIb*. H_2 from Coal for Urea Manufacture + CC CBM Power (CBM Produced by Injecting into Deep Coal Beds CO_2 Generated in Making H_2)[a]
	NH_4NO_3	Urea		
Coal consumption rate (PJ/y)	69.87	52.45		
CBM use in producing H_2 from coal (PJ/y)	-		33.28	
CBM use in external electricity generation (PJ/y)	-		7.59	
Rate of producing H_2 from coal (PJ/y)			20.77	7.39
CO_2 available (kgC/GJ_{H2})	25.76			
Use of available CO_2?	29.70	15.69	29.70	15.69
CBM production rate (PJ/y)	Vented to Atmosphere		Injected into Deep Coal Beds to Stimulate Production of CBM	
Electricity production rate (TWh/y)	-		28.36	14.98
Rate of electricity export (TWh/y)	3 509	1 792	3.824	1.958
Coal price ($/GJ)	2.666	0.949	2.666	0.949
CBM production cost ($/GJ)[b]	1 0			
H_2 production cost ($/GJ)[c]	-		1.78	1.75
Electricity production cost (cents/kWh)[d]	7.34		7.17	7.16
CO_2 emissions, H_2 production (kgC/GJ)[c]	2 82		2.23	2.20
CO_2 emissions, electricity generation (grC/kWh)[c]	38 63		26.06	
System CO_2 emissions (10^6 kgC/y)[c]	235.6		- 104.5	
	1623	1218	393	572

[a] In the Base Cases coal is used both as feedstock and for providing external electricity (@ 35.5% efficiency) and heat (@ 80% efficiency) requirements in H_2 manufacture. In the other cases (Case IIa is shown in Figure 6) 85%-efficient CBM boilers are used to provide the external heat and 50.2%-efficient CBM-fired combined cycles are used to provide the external electricity required in H_2 manufacture, and coal is used only as a feedstock.

[b] The CBM production costs are developed according to the procedure for Case Ia presented in Table 4.

[c] For H_2 pressurized to 300 bar. See Table 6 for the Base Case calculation. Costs are somewhat lower for the other cases because the required electricity is provided by CBM combined cycle plants that provide electricity at lower cost than coal steam-electric plants.

[d] Assumed installed capital costs [\$963/kW$_e$ for coal steam-electric plants and \$413/kW$_e$ for CBM combined cycle (CC) plants] and O&M costs (\$0.0041/kWh for coal steam-electric plants and \$0.0035/kWh for CBM CC plants) are from a recent General Electric study (Stoll and Todd, 1997). Capital charge rates of \$0.0140/kWh for coal steam-electric plants and \$0.0060/kWh for CBM CC plants are calculated assuming these capital costs, a 10% discount rate, a 25-year plant life, a 0.5%/year insurance charge, and a 90% capacity factor.

[e] [illegible]

Table 3. Energy & Mass Balances for the Production of CBM via Injection into a Deep Coal Bed of CO_2 Produced as a Byproduct of H_2 Manufactured from Coal and CBM, *Case Ia*	
CO_2 injection rate for CBM-derived H_2 production, tCO_2/h[a]	104.9
CO_2 injection rate for coal-derived H_2 production, tCO_2/h[b]	355.3
Total CO_2 injection rate, tCO_2/h (kmol CO_2/h; kgC/GJ_{CBM})	460.2 (10.460; 26.98)
CBM production rate, PJ_{CBM}/y (kmol/h)	36.73 (5,230)
Electricity requirements, 10^6 kWh/y (kWh/GJ_{CBM})	
CO_2 compression, 1.3 to 100 bar[d]	287.6 (7.83)
CBM compression, 1 to 30 bar[e]	119.7 (3.26)
Total electricity requirements	407.3 (11.09)

[a] For H_2 produced at a rate of 21.12 PJ/y from CBM via steam reforming. The sequestration rate is 10.69 kgC/GJ_{H2} (Williams, 1996), and the CBM gas feedstock required is 1.114 GJ_{CBM} per GJ_{H2} (Williams et al., 1995).

[b] For H_2 produced at a rate of 25 76 PJ/y from coal via oxygen-blown gasification. The sequestration rate is 29.70 kgC/GJ_{H2} (Williams, 1996), and the coal feedstock required is 1.292 GJ_{COAL} per GJ_{H2} (Williams et al., 1995).

[c] Following Gunter et al. (1997) it is assumed that 1 kmol of CBM is recovered for each 2 kmols of CO_2 injected into and sequestered in the deep coal bed from which the CBM is recovered.

[d] It is assumed that CO_2 recovered from the PSA units @ 1.3 bar is compressed to 100 bar for pipeline transmission and injection into the coal bed, as would be the case for CO_2 injection into depleted natural gas fields (Blok et al., 1997). The electricity required is 78.06 kWh per tonne for compression to 80 bar (the supercritical point is 73.8 bar, 31°C) plus 0.057 kWh/tonne/bar for additional pressure. The pressure has to be sufficiently high to prevent two-phase flow problems during transmission; pressure losses in transmission amount to 0 12 bar/km. The electricity required = 79.19 kWh/tonne CO_2 or (79.19 kWh/tCO2*545.2 tCO2/h*0.9*8766 h/y)/(43.5*10^6 $GJ_{CBM}/_y$) = 7.83 kWh/GJ_{CBM}.

[e] It is assumed that CBM is recovered at 1 bar and compressed to 30 bar at the wellhead Assuming a compressor efficiency nc = 0 85 and N = 4 stages of compression, the electricity required to compress 1 GJ (Q = 920.8 scf) of CH_4 (for which the ratio of specific heats k = 1.315) is $7.9795 \times 10^{-4} \times Q \times (N/nc) \times k/(k-1) \times [(P2/P1)^{(k-1)/(Nk)} - 1]$ = 3.26 kWh/GJ_{CBM}

Table 4. Estimated Production Cost for CBM Recovered from Deep Coal Beds via CO_2 Injection, *Case Ia*	
CO_2 injection rate, tCO_2/h[a]	460.2
CBM production rate, PJ/y[a] (GJ/h)	36.73 (4656)
Capital costs related to CO_2 injection (10^6 \$)	
CO_2 compressor[b]	28.16
CO_2 injection wells[c]	33.12
CO_2 pipelines[d]	20.02
Utilities, auxiliaries[e]	20.33
Engineering, administrative support, contingencies, owner costs, fees, profits, startup[f]	50.82
Subtotal	152.45
Capital costs related to CBM recovery (10^6 \$)	
Geological/geophysical expenditures, engineering feasibility studies[g]	6.00
CBM production wells[h]	49.82
Surface equipment, including gas gathering equipment[i]	24.00
Water disposal[j]	10.00
CBM compressor[k]	13.66
Engineering, administrative support, contingencies, owner costs, fees, profits, startup[f]	51.74
Subtotal	155.22
Total capital cost	307 67
Production cost (\$ per GJ_{CBM})	
Capital costs[l]	
Related to CO_2 injection	0.485
Related to CBM recovery	0.489
O&M costs	
Related to CO_2 injection[m]	0.083
CBM wells, gas treatment, water disposal, engineering, general & overhead[n]	0.277
Electricity requirements	
For CO_2 compression[o]	0.187
For CBM compression[o]	0.078
Royalty to resource owner[p]	0.200
Total production cost	1.799

[a] For the CBM recovery system described for Case Ia in Table 3 It is assumed that all costs of CO_2 disposal downstream of the PSA units at the H_2 production plants (for CO_2 compressor, CO_2 pipelines and CO_2 injection wells), as well as CBM recovery costs and royalties are levelized over the 25-year life of the CBM recovery system and charged to the cost of CBM It is assumed that the CBM is recovered from an array of 200 wells in a circular 130 km^2 field (so that the recovery field area per CBM recovery well is 65 hectares), at the center of which the energy conversion facility is located. It is assumed that the wells are arranged such that aggregate output of all the wells can be maintained at a relatively constant level over the assumed 25-y life of the CBM recovery facility. With 200 wells the average CBM recovery rate is 12,700 Nm³ ([illegible] million scf) per day per well, so that the ultimate recovery is 1 78 million Nm^3 (66 million scf) per hectare.

[b] The estimated compressor cost (for compressing CO_2 from 1.3 to 100 bar) is \$61,200/(tonne/h) (Blok et al., 19[illegible]

[c] The number and spacing of CO_2 injection wells depends on the injection rate per well. The feasible CO_2 injection rate per well depends directly on the coal bed thickness and the bed's permeability to the flow of CO_2, according to the procedure outlined in footnote 23 (main text), where it is shown that the CO_2 flow rate per well is 28.2 tonnes/h, so that 460.2/28.2 = 16 CO_2 injection wells are required Following Hendriks (1994), it is assumed that the cost of a CO_2 injection well (in 10^6 \$) is 0.00125*D + 1 = \$2.07 million, so that the total capital cost for the CO_2 injection wells is \$33.12 million.

Notes to Table 4, cont.

Since the recovery field is assumed to be a circle of radius 6.43 km, the average distance from the energy conversion facility to a CO_2 injection well and thus the average length of a CO_2 pipeline = (2/3)*6.43 = 4.29 km. The pipeline cost I_{PIPE} (in $) is estimated according to $I_{PIPE} = 0.56 \times (300 + 1500 \times d^{0.9}) \times L$ (Blok et al., 1997), where d = diameter (in m), L = length (in m). The optimal diameter is d = 0.5 for a CO_2 injection rate of 500 t/h; assuming the cross-sectional area is proportional to the flow rate, $d = 0.5 \times (28.2/500)^{0.5} = 0.119$ m. Thus the cost of 16 pipelines of average length 4.29 km is
$I = 16 \times 0.56 \times (300 + 1500 \times 0.119^{0.9}) \times 4290$ = $20.02 million.

Assumed to be 25% of other equipment costs, following Williams et al. (1995a).

Assumed to be 50% of direct capital costs.

Following a Kuuskraa and Boyer (1993) analysis of CBM recovery in the San Juan Basin, it is assumed that geological and geophysical expenditures and engineering-based feasibility studies cost $30,000 per CBM recovery well, or $6.00 million for 200 wells.

It is assumed that the average well depth is 856 m [the average for all CBM wells drilled in the United States in 1990 (Petzet, 1991)] and that CBM well costs are same as the average for all CBM wells drilled in the United States in 1990, some $291 per m (Petzet, 1991). Thus the cost for 200 CBM production wells is $49.82 million.

Following the Kuuskraa and Boyer (1993) analysis for the San Juan Basin, it is assumed that surface equipment, including gas gathering cost $120,000 per CBM recovery well, or $24.00 million for 200 wells.

Following the Kuuskraa and Boyer (1993) analysis for the San Juan Basin, it is assumed that water disposal costs $50,000 per CBM recovery well, or $10.00 million for 200 wells; this estimate includes costs for water treatment and injection of recovered water into disposal wells.

It is assumed that the CBM is recovered at 1 bar and compressed to 30 bar. The CBM compressor capacity Pcm (in kW_e) needed is $Pcm = 7.9795 \cdot 10^{-4} \cdot Q \cdot (N/nc) \cdot k/(k-1) \cdot [(P2/P1)^{(k-1)/Nk} - 1]$, where Q is the CBM flow rate in scf/h, P2 and P1 are the output and input pressures, respectively, nc is the compressor efficiency, k is the ratio of specific heats, and N is the number of stages of compression. For methane, k = 1.315 and 1 scf = 1086 kJ or 1 GJ = 920.8 scf, so the flow rate is $Q = 4.287 \cdot 10^6$ scf/h. Assuming that N = 4 and nc = 0.85, the needed capacity Pcm = 15,182 kW_e. Assuming that compressors cost $900/$kW_e$ (Williams et al., 1995a), the required capital is $13.66 million.

Assuming a 10% discount rate plus a 0.5%/y insurance charge for equipment, annual capital charge rates are 0.110 (25-y project life) for studies, 0.122 for compressors (20-y equipment life), and 0.115 for other capital (25-y equipment life).

Assumed to be 3% of capital costs for equipment per year.

Adapted from a Kuuskraa and Boyer (1993) analysis of CBM recovery in the San Juan Basin.

The electricity needs for CO_2 and CBM compression are 7.83 kWh/G_{CBM} and 3.26 kWh/GJ_{CBM}, respectively (see Table 3). It is assumed that electricity is produced in a 194.4 MW_eCBM combined cycle power plant dedicated to meeting the electricity requirements for CBM production plus H_2 production from CBM and coal, according to the scheme indicated in Table 1. Capital costs for power generation are calculated assuming a 10% discount rate, a 25-year plant life, a 0.5%/year insurance charge, and a 90% capacity factor. It is assumed that the installed capital cost is $413/$kW_e$ (so that the capital charge is $0.0060/kWh) the O&M cost is $0.0035kWh, and the efficiency is 45% (so that the fuel cost is $0.0144/kWh with a CBM cost of $1.80/GJ); the total cost of CBM-derived electricity is $0.0239/kWh. Except for fuel costs and the assumed combined cycle efficiency, these power plant cost parameters are based on a recent study by General Electric analysts (Stoll and Todd, 1997). The combined cycle plant considered in that study is for a 506 MWe Frame 7FA system with a 50.2% efficiency. The lower 45% efficiency assumed here is a more appropriate value at the smaller plant size considered here.

Assumed to be 12.5% of direct CBM costs.

Table 5. Energy and Mass Balances for the Production of H_2 from Coal and CBM, *Case Ia*		
	H_2 from Coal	H_2 from CBM
Annual H_2 production (PJ/y)	25.76	21.12
Byproduct CO_2 (kgC/GJ_{H2})	29.70	10.69
Feedstock required[a] (GJ/GJ_{H2})	1.292	1.114
Electricity requirements (kWh/GJ_{H2})		
For producing O_2 for the coal gasifier[b]	16.74	-
Lockhopper[c]	0.58	-
PSA recycle compressor[c]	3.87	3.26
Vacuum pump for PSA unit[d]	11.03	3.97
H_2 compression[e]	8.42	8.42
Pumps	0.11	0.05
Total	40.75	15.70
Electricity supplies[f,g] (kWh/GJ_{H2})		
Waste heat	3.08	2.30
Purge gases	4.95	-
External sources	32.72	13.40
External heat requirements[h] (GJ/GJ_{H2})	0.031	-

[a] From Table 4 in Williams et al. (1995a). Does not include process energy.

[b] Some 480 kWh of electricity is required to produce a tonne of O_2 at 24.50 bar via air liquefaction, and the O_2 requirements for coal gasification are 0.03488 tonnes/GJ_{H2} (Williams et al., 1995a), so that the electricity required is 0.03481*480 = 16.74 kWh/GJ_{H2}.

[c] Electricity requirements for the lockhopper, the PSA recycle compressor, and pumps are from Williams et al (1995a).

[d] The electricity required for the vacuum pump for the PSA unit can be calculated as 4.46 kWh/(kmol CO_2 removed)[see footnote c, Table 4 in Williams et al. (1995a)], which amounts to
(4.46 kWh/kmol CO_2)*(3908/5529)/(0.28583 GJ/kmol) = 11.03 kWh/GJ_{H2} in the case of H_2 from coal and
(4.46 kWh/kmol CO_2)*(0.8552/3.3642)/(0.28583 GJ/kmol) = 3.97 kWh/GJ_{H2} in the case of H_2 from CBM.

[e] The H_2 is recovered from the PSA unit at 20.3 bar. For NH_3 production it is assumed that H_2 must be compressed to 300 bar (N = 3). The power required for compression (in kW) is:
$Pcm = 7.9795*10^{-4}*Q*(N/nc)*k/(k-1)*[(P2/P1)^{(k-1)/Nk}-1]$, where Q is the flow in scf/h, N is the number of stages of compression, nc is the compressor efficiency, k is the specific heat ratio, and P2 and P1 are, respectively, the ouput and input pressures. For H_2, 1 scf = 343 kJ or 1 GJ = 10^6 kJ = 2915.45 scf. Thus the electricity required EL_{H2} (in kWh per GJ_{H2}) is $EL_{H2} = 2.3264*(N/nc)*k/(k-1)*[(P2/P1)^{(k-1)/Nk}-1]$. Assuming nc = 0.85 and k = 1.411 for H_2, the electricity requirements for compressing 1 GJ of H_2 to 300 bar are: $2.3264*(3/0.85)*1.411/(0.411)*[(300/20.3)^{(0.411)/4.233} - 1] = 8.42$ kWh/GJ_{H2}

[f] Some 3.08 kWh/GJ_{H2} is provided by waste heat recovery and 4.95 kWh/GJ_{H2} is provided by purge gases [see Table 4 in Williams et al. (1995a)].

[g] Some 2.30 kWh/GJ_{H2} is provided by waste heat recovery [see Table 4 in Williams et al. (1995a)].

[h] See Table 4 in Williams et al. (1995a).

Table 6. **Estimated Production Costs for H_2 Produced from Coal (*Base Case*) and CBM (*Case Ia*)**		
	H_2 from Coal[a,b]	H_2 from CBM[a,c]
production rate, PJ_{H2}/y (GJ_{H2}/h)	25.76 (3,265)	21.12 (2,677)
Feedstock input rate, PJ/y (GJ/h)	33.28 (4.219)	23.52 (2,982)
Installed equipment cost (10^6 \$)[d]		
Feed preparation[e]	52.00	-
Gasifier[f]	91.86	-
High-temperature gas cooling[g]	86.67	-
Oxygen plant[h]	72.68	-
Sulfur removal[i]	27.74	-
Reformer[j]	-	46.51
Shift reactors[k]	5.68	9.63
PSA recycle compressor[l]	11.37	7.85
PSA unit (with CO_2 removal)[m]	39.30	33.08
Hydrogen compressor[n]	24.74	20.29
Steam turbine cogeneration plant[o]	29.27	11.80
Utilities, auxiliaries[p]	110.33	32.29
Subtotal	551.64	161.45
Contingencies, owner costs, fees, profits, startup[q]	193.07	56.51
Total fixed capital investment (10^6 \$)	744.71	217.96
Working capital (10^6 \$)[r]	55.16	16.15
Land (10^6 \$)[s]	4.77	4.23
Production Cost (\$/GJ_{H2})		
Capital[t]	3.57	1.30
Feedstock[u]	1.29	2.00
Operation and maintenance[v]	1.52	0.62
Purchased electricity[w]	0.92	0.32
Other purchased energy[x]	0.04	-
Total production cost (\$/GJ_{H2})	7.34	4.24

The costs presented here are for systems operated at 90% capacity factor and having the energy balances presented in Table 5.

For the case presented here (the Base Case in Table 1) coal is used to provide external electricity and heat needs as well as feedstock requirements for H_2 manufacture.

The indicated level of H_2 production from CBM is for Case Ia, where (*i*) all byproduct CO_2 from producing H_2 from coal and CBM (see Table 1 and Figures 4 and 5) is injected into deep coal beds to produce CBM (with the molar production rate of CBM equal to half the molar CO_2 injection rate into the coal beds, (*ii*) the recovered CBM is used both as a feedstock for producing H_2 and to provide the external electricity and heat needs in the production of H_2 from both CBM and coal.

Capital costs presented here are based on costs developed in Williams et al (1995a) for producing H_2 from coal at a rate of 37.76 PJ/y and from natural gas at a rate of 19.09 PJ/y, adjusted to the production rates in the present analysis using scaling factors for system components presented in Williams et al. (1995a).

The capital cost for coal feed preparation is $(25.76/37.76)^{0.7} * 67.96$ = \$52.00 million.

The capital cost for a Shell oxygen-blown coal gasifier is $(25.76/37.76)^{0.7} * 120.6$ = \$91.86 million.

Notes for Table 6, cont.

g The capital cost for high-temperature gas cooling is $(25.76/37.76)^{0.7}*113.27$ = \$86.67 million.

h The capital cost for the oxygen plant $0.260*(\mathrm{tO2/d})^{0.712}$ million \$. The O_2 requirements for the coal gasifier are (25.76/37.76)*3.03*(1719 kmol/h)*(32 kg/kmol)/(1000 kg/t)*(24 h/d) = 2728.94 t/d. Thus the capital cost is \$72.68 mi...

i The capital cost for sulfur removal is $(25.76/37.76)^{0.7}*36.25$ = \$27.74 million.

j The capital cost for a steam reformer is $(21.12/19.09)^{0.57}*43.91$ = \$46.51 million.

k The capital costs for shift reactors are $(25.76/37.76)^{0.65}*7.28$ = \$5.68 million for coal and $(21.12/19.09)^{0.65}*9.0...$ \$9.63 million for CBM.

l Based on PSA recycle compressor electricity requirements presented in Table 5, the compressor capacity needed the PSA recycle compressor is [3.87 kWh/GJ_{H2})]*(3,265 GJ/h) = 12,636 kW_e for coal and [3.26 kWh/GJ_{H2})]*(2,677GJ/h) = 8,727 kW_e for CBM (Williams et al., 1995a), the capital cost for these compressors is \$11.37 million for coal and \$7.85 million for CBM.

m The capital cost for the Gemini-9 PSA unit (with CO_2 removal) is $(25.76/37.76)^{0.7}*51.39$= \$39.30 million for coal and $(21.12/19.09)^{0.7}*30.82$ = \$33.08 million for CBM.

n The H_2 compressor capacity needed is (3,265 GJ/h)*(8.42 kWh/GJ_{H2}) = 27,491 kW_e for coal and (2,677 GJ/h)*(8.42 kWh/GJ_{H2}) = 22,540 kW_e for CBM. Assuming that H_2 compressors cost \$900/kW_e, the capital cost is \$24.74 million for coal and \$20.29 million for CBM.

o The capital cost for the steam turbine cogeneration plant is $(25.76/37.76)^{0.626}*37.19$ = \$29.27 million for coal and $(21.12/19.09)^{0.626}*37.19$ = \$11.80 million for CBM.

p Utilities and accessories are assumed to cost 25% of the above equipment costs

q Contingencies, owner costs, fees, profits, and startup costs are assumed to be 35% of equipment costs

r The required working capital is assumed to be 10% of the equipment cost.

s Following Williams et al. (1995a) land costs are assumed to be $423*(\mathrm{tpd})^{1.147}$ for coal, where tpd is the coal feedstock input rate in tonnes per day, and \$0.18 per day GJ/y of CBM input in the CBM case. In the present coal case the coal input rate is 5000*(25.76/37.76) = 3411 tpd, so that the land cost is \$4.77 million; in the CBM case the land cost is \$4.23 million.

t Assuming a 10% discount rate, equipment lifetimes of 20 years for compressors and 25 years for other equipment and a 0.5%/year insurance charge rate, the annual capital charge rates are 0.122 for compressors and 0.115 for other equipment. Both working capital and land are non-depreciating assets for which the annual capital charge rate is 0.10

u Feedstock costs are assumed to be \$1.00/GJ for coal and \$1.80/GJ for CBM (see Table 4).

v Operation and maintenance (O&M) costs are derived as follows from the values presented in Williams et al. ... for H_2 derived from coal and natural gas in the amounts 37.76 PJ/y and 19.09 PJ/y, respectively. It is assumed: that the ... of labor scales with output [(25.76/37.76)*3.14 = \$2.14 million/y for coal and (21.12/19.09)*1.0 = \$1.11million/y for CBM]; that maintenance is 3% of the installed hardware cost (0.03*551.64 = \$16.55 million/y for coal and 0.03*161.45 = \$4.84 million/y for CBM); that direct overhead is 45% of the labor cost (0.45*2.14 = \$0.96 million/y for coal and 0.45*1.11 = \$0.50 million/y for CBM); that general overhead is 65% of labor + maintenance cost [0.65*(2.14 + 16.55) = \$12.15 m... for coal and 0.65*(1.11 + 4.84) = \$3.87 million/y for CBM]; and that catalysts and chemicals scale with output (25.76/37.76*10.87 = \$7.42 million/y for coal and 21.12/19.09*2.58 = \$2.85 million/y for CBM). Thus total O&M ... amount to \$39.22 million/y for coal and \$13.17 million/y for CBM.

Notes for Table 6, cont.

- External electricity requirements amount to 32.72 kWh/JG_{H_2} with coal and 13.40 kWh/JG_{H_2} with CBM (see Table 5). Capital costs for power generation are calculated assuming a 10% discount rate, a 25-year plant life, a 0.5%/year insurance charge, and a 90% capacity factor. In the coal case, it is assumed that electricity is produced in a 500 MW_e coal steam-electric plant with an installed capital cost of \$963/kW_e (so that the fuel cost is \$0.0101/kWh with a coal cost of \$1.0 GJ); thus the total cost of coal-derived electricity is \$0.0282/kWh. In the CBM case, it is assumed that electricity is produced in a CBM-fired combined cycle power plant with an installed capital cost of \$413/kW_e (so that the capital charge is \$0.0060/kWh), an O&M cost of \$0.0035/kWh, and an efficiency of 45% [so that the fuel cost is \$0.0144/kWh with a CBM cost of \$1.80/GJ (see Table 4)]; thus the total cost of CBM-derived electricity is \$0.0239/kWh. Except for fuel costs and the assumed combined cycle efficiency, these power plant cost parameters are based on a recent study by General Electric analysts (Stoll and Todd, 1997). The combined cycle plant considered in that study (which involves use of a GE Frame 7FA gas turbine) has a capacity of 506 MW_e and a 50.2% efficiency. The lower 45% efficiency assumed here is a more appropriate value at the smaller plant size considered here (194 MW_e).

- It is assumed that the external heat required for making H_2 from coal (0.031 GJ/GJ_{H_2}) is provided by burning coal costing \$1.0/GJ in an 80%-efficient boiler.

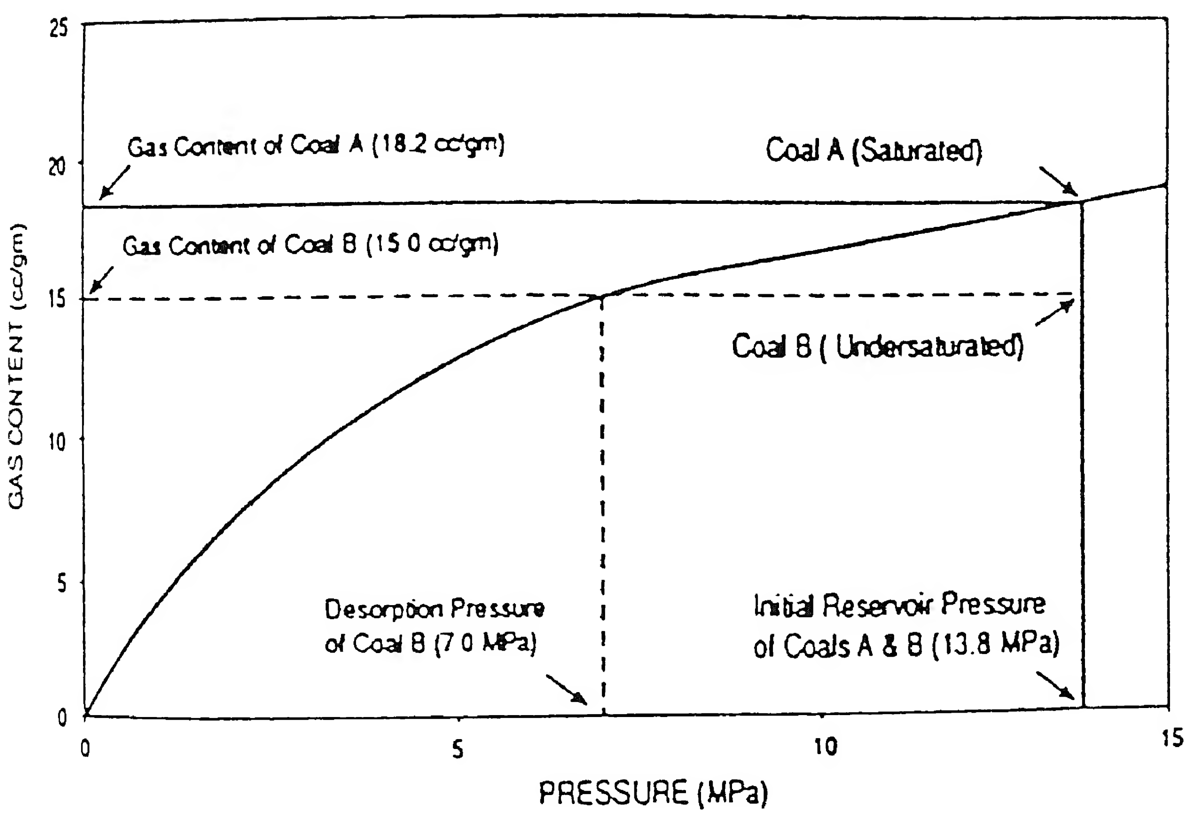

Figure 1: **Idealized Coalbed Gas Sorption Isotherm Showing Relationship between Reservoir Pressure and Gas Content for a Saturated Coal (A) and an Unsaturated Coal (B)**

The curve shows that maximum amount of gas that can be stored at a given reservoir pressure. It can be used to understand the gas desorption process associated with the CBM recovery technique that involves reservoir depressurization (e.g. via dewatering). For coal A, which contains 18.2 cm^3 of gas per gram of coal at a reservoir pressure of 13.8 MPa, gas would immediately begin desorbing from the coal matrix when the coal is penetrated by a drill bit and the pore pressure begins to drop. For coal B, which is unsaturated with methane at 15.0 cm^3 per gram and a pressure of 13.8 MPa, gas desorption would not begin until the reservoir pressure is reduced to 7.0 MPa.

Sources: Rice et al. (1993).

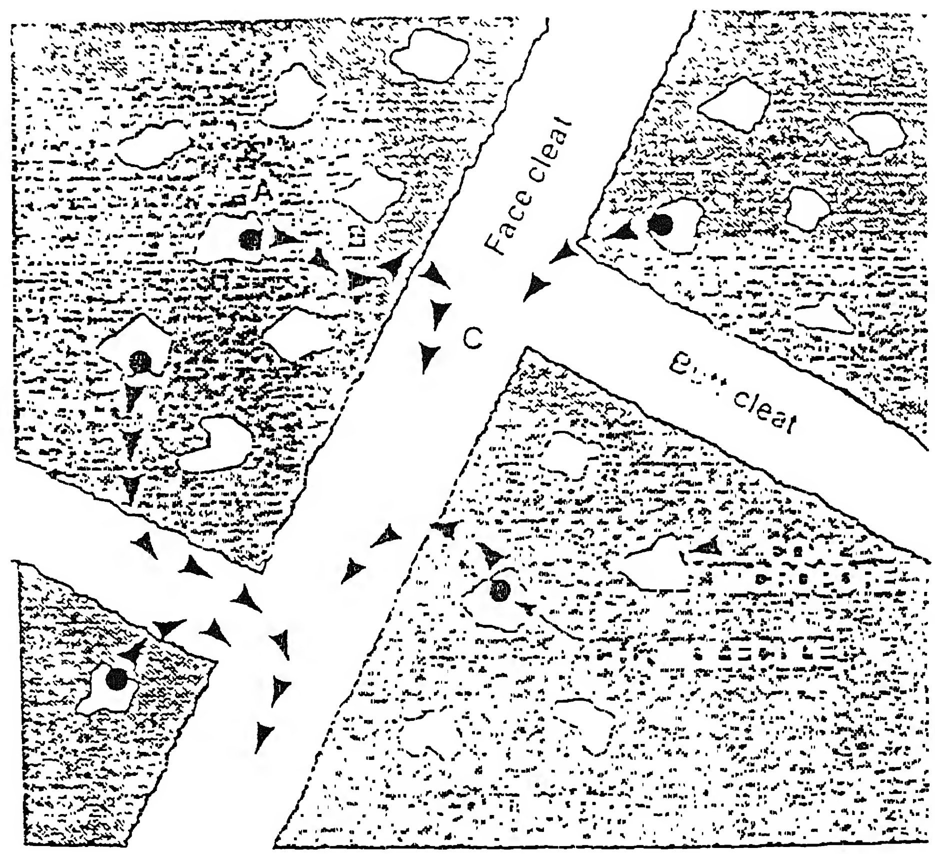

Figure 2: Diagram Showing (A) Desorption of Methane from Micropores in Coal As a Result of Reservoir Depressurization, (B) Diffusion Path of Methane Through the Coal Matrix, and (C) Flow of Methane in Through Fractures in the Coal Bed

Source: Rice et al. (1993).

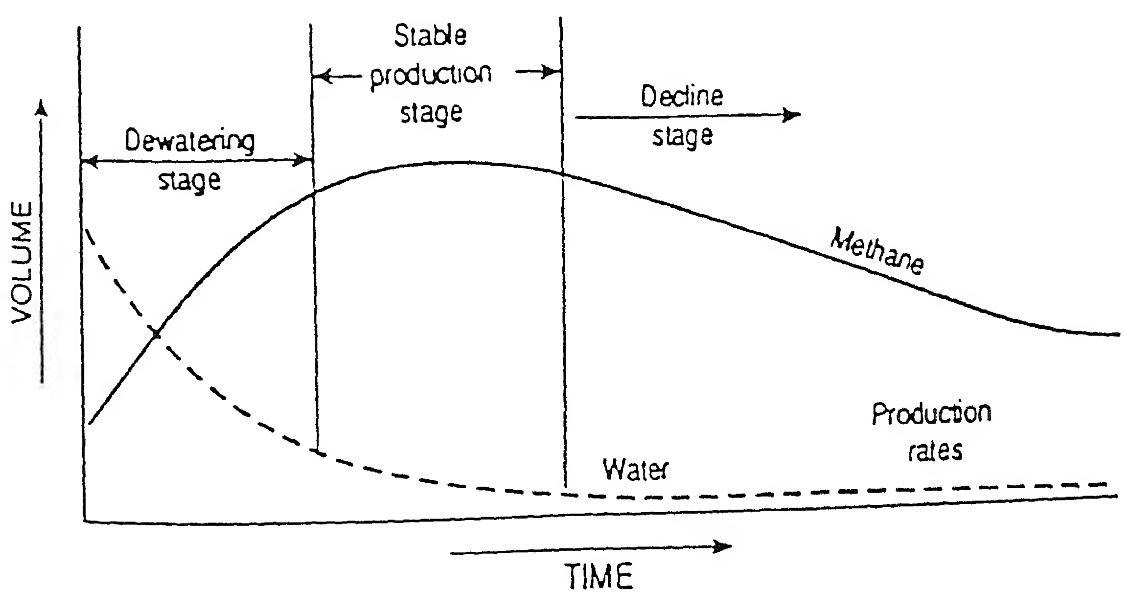

Figure 3: Generalized Production History Showing Volumes of Methane and Water Over Time for a Typical Coalbed Gas Well Based on Reservoir Depressurization

Source: Rice et al. (1993).

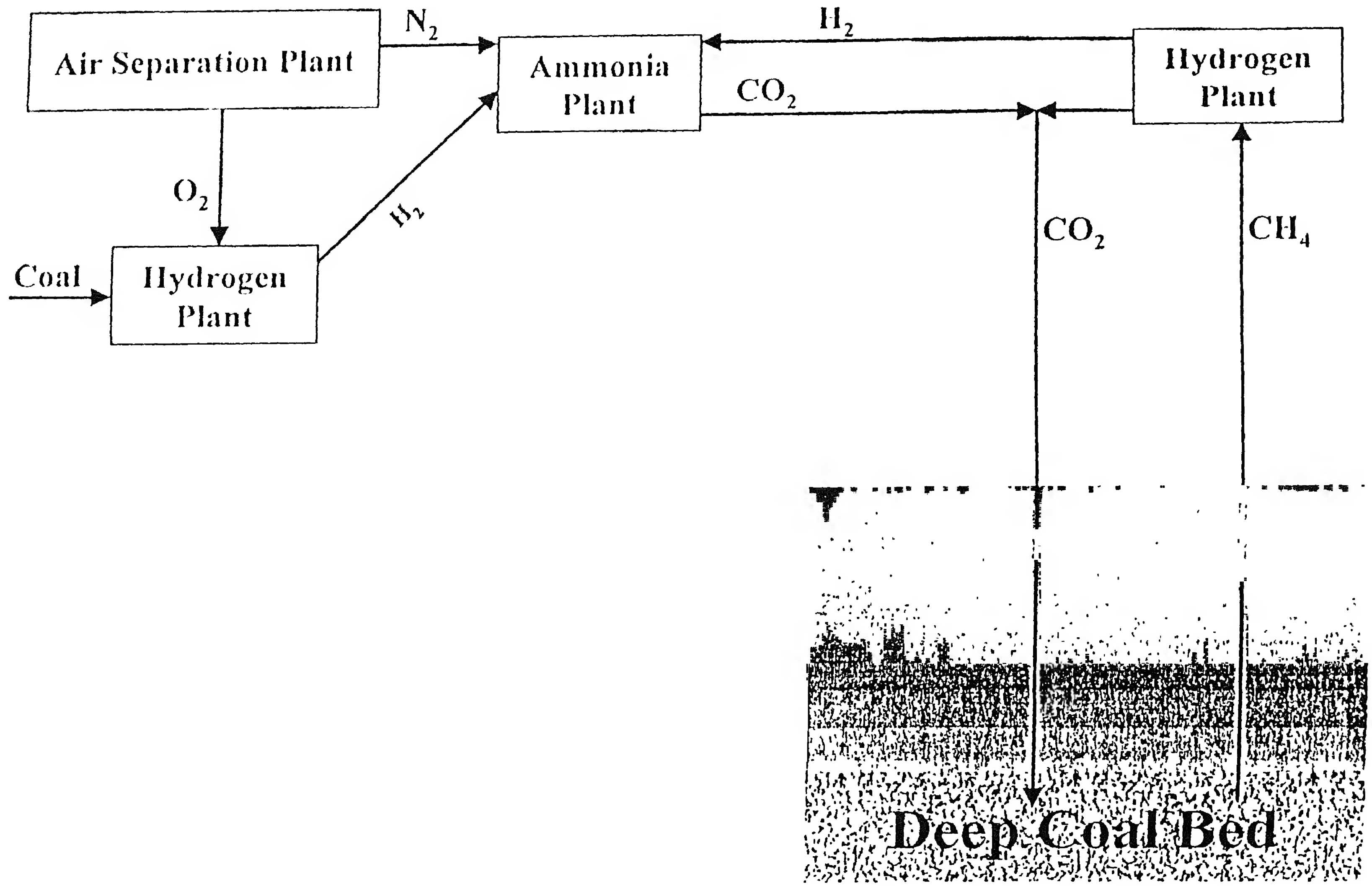

Figure 4: Schematic for the Production of H_2 from CBM and Coal for Ammonia Manufacture, Using all the CO_2 Separated at the H_2 Production Plants to Recover CBM, with Sequestration of the Injected CO_2 in the Coal Bed (*Case Ia in Table 1*)

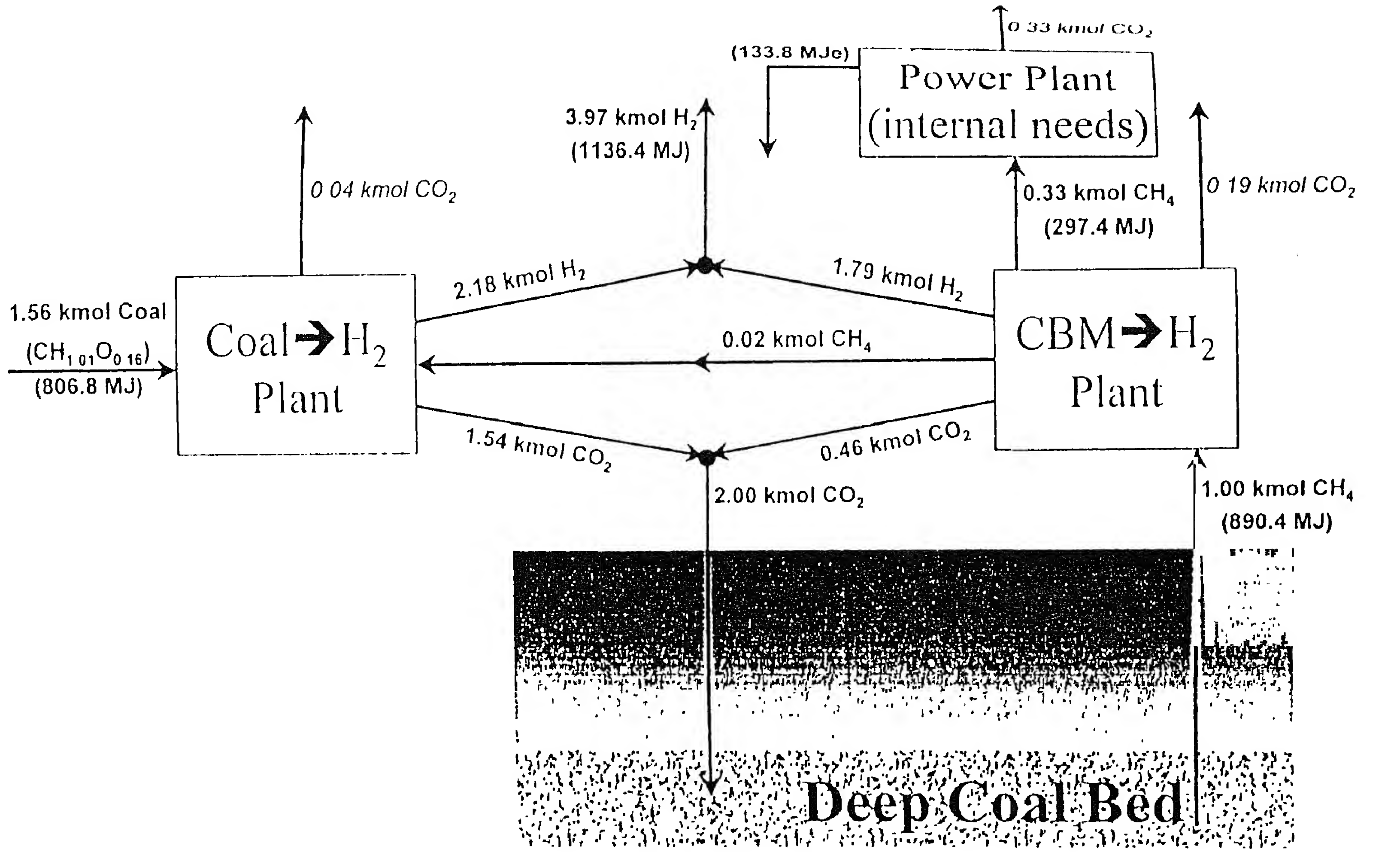

Figure 5: Material and Energy Balances for H_2 Production from Coal and Coal Bed Methane (CBM), Using All the CO_2 Separated at the H_2 Production Plant to Recover CBM, with Sequestration of the Injected CO_2 in the Coal Bed

For H_2 compressed to 300 bar, as would be required for ammonia manufacture. These balances (per kmol of CBM recovered from the coal bed) are for Case Ia in Table 1. The ratio of H_2 produced from the CBM feedstock to that produced from coal is for the situation where a 2/1 molar ratio for CO_2 injection to CBM recovery is realized. Some of the recovered CBM is used to provide the electricity needed to make H_2 from coal and CBM, to provide the electricity needed for CBM recovery, and to provide the external heat needed in the manufacture of H_2 from coal.

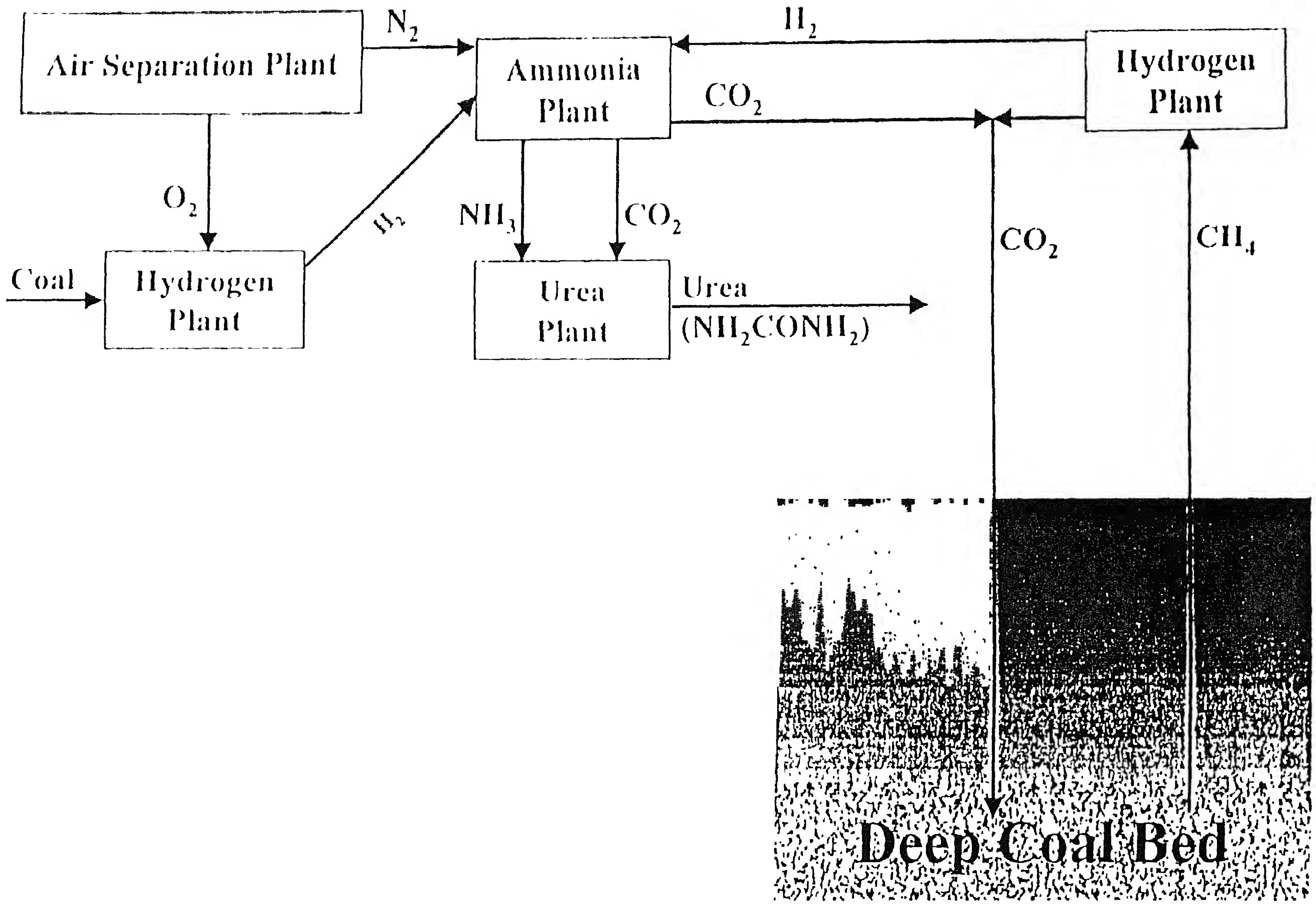

Figure 6: Schematic for the Production of H_2 from CBM and Coal for the Manufacture of Ammonia and Urea, Using Byproduct CO_2 Separated at the H_2 Production Plants in Excess of that Needed for Urea Manufacture to Recover CBM, with Sequestration of the Injected CO_2 in the Coal Bed (*Case Ib in Table 1*)

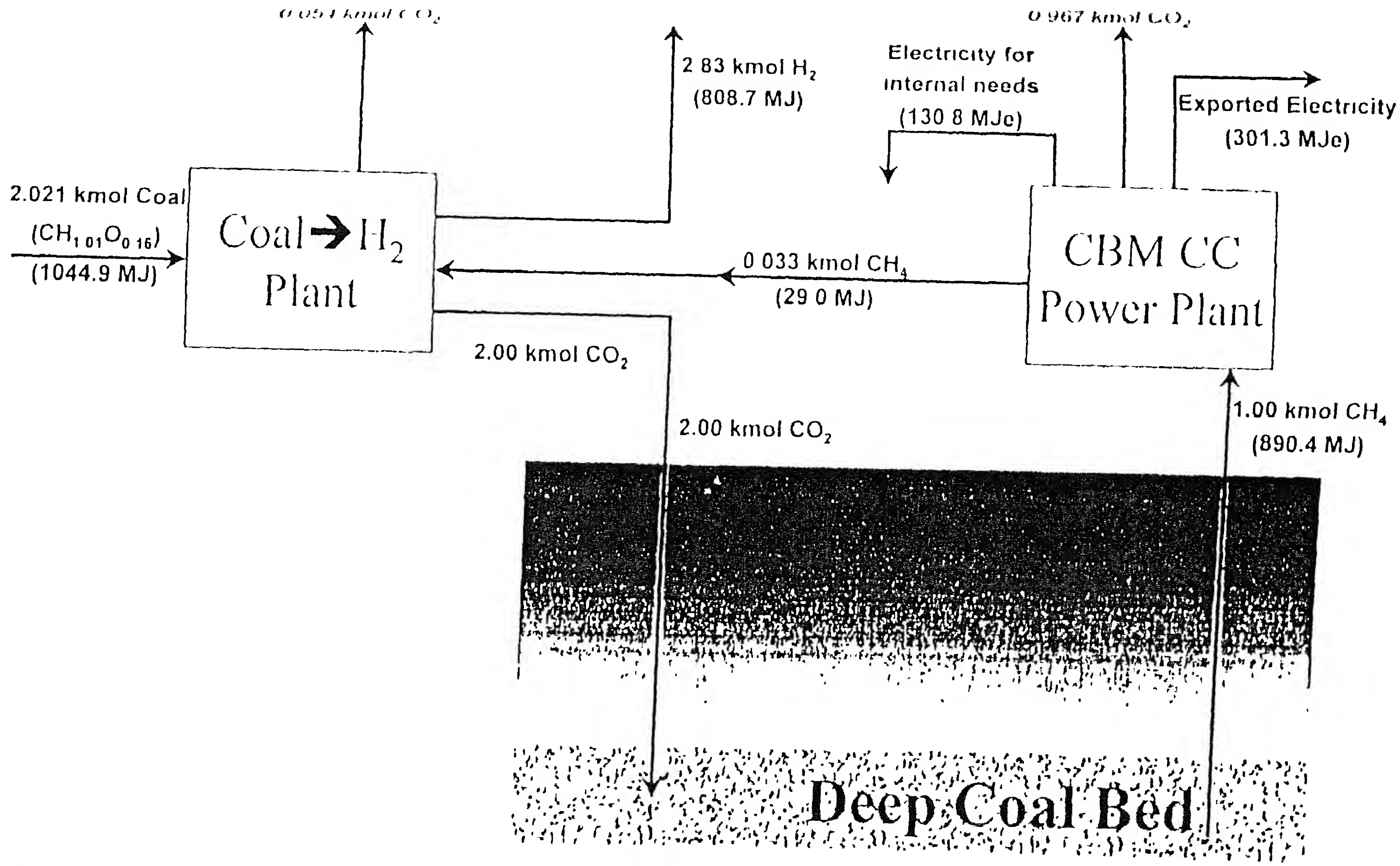

Figure 7: Material and Energy Balances for H_2 Production from Coal + Electricity Generation from CBM in a Combined Cycle Power Plant, Using the CO_2 Separated at the H_2 Production Plant to Recover CBM, with Sequestration of the Injected CO_2 in the Coal Bed

For H_2 compressed to 300 bar, as would be required for ammonia manufacture. These material and energy balances (per kmol of CBM recovered from the coal bed) are for Case IIa in Table 2. The ratio of H_2 production from the coal feedstock to the electricity production from CBM is for the situation where a 2/1 molar ratio for CO_2 injection to CBM recovery is realized. Some of the recovered CBM is used to provide the electricity needed to make H_2 from coal and CBM, to provide the electricity needed for CBM recovery, and to provide the external heat needed in the manufacture of H_2 from coal; the rest of the recovered CBM is used to make electricity for export from the site.

Prospects for Reducing GHG Emissions in Coal Systems

Prepared by
The Scientific and Technical Advisory Panel (STAP)
of the Global Environment Facility (GEF)

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PREFACE

It is a pleasure to present the report **Prospects for Reducing GHG Emissions in Coal Systems** prepared by STAP in response to the request of the GEF Council that STAP advise the Council about opportunities for reducing Greenhouse Gas (GHG) Emissions from coal systems.

In preparing this report STAP convened at workshop on Options for Improving Coal Supply Systems to Reduce Greenhouse Gas Emissions at the Institute for Environmental Studies, Vrije University, Amsterdam, 16-17 June 1997, in conjunction with the Ninth Meeting of STAP. This workshop was organized and chaired by Dr Charles J Johnson of the East West Center, Honolulu and brought together coal experts from around the world. This STAP report is based on discussion at the workshop, the workshop report prepared by Dr Johnson (Report of the STAP Workshop on Options for Improving Coal Supply Systems to Reduce Greenhouse Gas Emissions), and additional analysis carried out by STAP.

This report was prepared by the STAP Working Group on Climate and Energy under the chairmanship of Dr Robert Williams

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ABSTRACT

In response to a request of the GEF Council that STAP advise the Council about opportunities for reducing greenhouse gas (GHG) emissions from coal systems. STAP (i) reviewed trends in coal consumption in selected major coal-consuming developing countries (ii) reviewed trends in coal-related emissions restrictions in developing countries, (iii) considered risks to GEF's renewable energy portfolio that might arise from the launching of a coal initiative, (iv) identified a systems approach as necessary in identifying the optimal sets of technologies for addressing the GHG emissions challenge for coal (v) reviewed alternative technologies and strategies for reducing GHG emissions and (vi) identified an evolutionary approach to coal that would facilitate the realization of deep reductions in GHG emissions over the longer term, while providing near and mid-term local environmental and economic benefits.

The STAP found because of the large and rapidly growing demand for coal particularly in Asia, the GEF should consider pursuing activities that could steer coal onto a more climate friendly path, if this could be done in ways that do not detract from GEF activities aimed at helping launch various renewable energy technologies in the global energy market. The concern about the potential impact on GEF's renewables activities of a new coal initiative relates to the fact that the GEF has very limited resources. As STAP has shown previously the characteristics of many renewable energy technologies are such that relatively modest resources of the scale that could be provided by GEF, appropriately targeted, could powerfully help launch the very embryonic renewable energy industries. In contrast, the world coal industry is large and coal projects tend to require much larger investments than do renewable energy projects. Only a few projects could potentially consume a significant share of GEF's resources available for addressing climate change. On the other hand, because large investments in coal are routinely made by the private sector in the developing world. GEF might be able to apply judiciously some of its very limited resources to reorient investments relating to coal in ways that are more compatible with climate change concerns. It may well be feasible and desirable for GEF to launch important new activities relating to coal in the context of existing GEF operational programs. Getting experience with coal activities this way would help ensure a proper balance between coal and renewable projects as GEF evolves a coal strategy and understands better what its comparative advantage is in helping steer coal along a more climate friendly path.

In the GEF decides to launch a program relating to coal, it should be in the context of a strategic plan in which near term actions are consistent with and supportive of long term objectives. Moreover, the GEF should take a systems approach to coal. Besides the CO_2 emissions from coal combustion, CO_2 and other GHG emissions from other parts of the coal system should be taken into account in appropriate lifecycle analyses. GEF should look for opportunities to reduce GHG emissions throughout the entire chain of activities ranging from mining through end-use, for synergisms between different supply options, for synergisms between coal and activities outside the coal industry, and for synergism between GHG mitigation goals and local environmental mitigation goals. This approach would help identify coal options that are sensible from local environmental and economic perspectives as well as helpful in dealing with the challenge of climate change.

Among the options reviewed by STAP were very low-cost actions that could be taken immediately, especially relating to the use of modern coal power plant management

techniques, that would reduce costs while providing some GHG emissions abatement. Also more energy efficient power generating technologies could be helpful in reducing emissions, although care must be taken to ensure that on a lifecycle basis, emissions reductions achieved through energy efficiency improvements are not offset by GHG emissions other than from coal combustion as might be the case for some fluidized bed combustion options.

STAP found that the option offering the greatest potential for using coal in a climate-friendly way is to separate the energy value of the coal from its carbon content, by decarbonizing the coal to produce hydrogen and by sequestering the CO_2 separated from the hydrogen at the production plant. While the widespread use of hydrogen as a fuel is not an imminent prospect, most of the technologies needed to embark on a coal decarbonizations/ CO_2 sequestration strategy are commercially available, and many activities that can be initiated today to facilitate a transition in the longer term to hydrogen could provide significant near-term local environmental and economic benefits. The key enabling technology for decarbonization is modern coal gasification technology, which offers multiple local environmental and economic benefits as well as climate benefits. Key initial steps in the development of a coal strategy designed around modern coal gasification technology are energy pricing reforms, reforms that encourage the use of coal-derived gas in combined heat and power applications, and effective local environmental policies. For coal-rich countries a key option for sequestration is injection of CO_2 into deep beds of unminable coal to recover coal bed methane as an energy source, a strategy that offers multiple local environmental and economic benefits as well as multiple climate-change benefits. A key initial step is to explore the potential for enhanced methane recovery from deep coal beds using excess CO_2 at plants that produce ammonia from coal; CO_2 sequestration would be a "free byproduct" of such activity. Most of what should be done in the near term relating to both decarbonization and sequestration would be desirable even if there were no climate-change challenge.

1. Introduction

In response to the request of the GEF Council that STAP advise the Council about opportunities for reducing greenhouse gas (GHG) emissions from coal systems. STAP (a) reviewed trends in coal consumption in selected major coal-consuming developing countries, (b) reviewed trends in coal-related emissions restrictions in developing countries, (c) considered risks to GEF's renewable energy portfolio that might arise from the launching of a coal initiative, (d) identified a systems approach as necessary in identifying the optimal sets of technologies for addressing the GHG emissions challenge for coal, (e) reviewed alternative technologies and strategies for reducing GHG emissions, and (f) identified an evolutionary approach to coal that would facilitate the realization of deep reductions in GHG emissions over the longer term, while providing near and mid-term local environmental and economic benefits.

A major part of the assessment process was a Workshop on Options for Improving Coal Systems to Reduce Greenhouse Gas Emissions that STAP convened at Vrije University in Amsterdam, 16-17 June 1997. The workshop, which brought together coal experts from around the world, was organised and chaired by Dr. Charles J. Johnson of the East-West Center in Honolulu. Participants from Australia, China, India, Japan, South Africa and the United States presented formal papers, and informal presentations were also made by observers from ABB Carbon AB, Council General des Mines of France, the International Energy Agency, and the World Bank.

2. Growth in coal consumption

Coal consumption has been growing at a rapid rate of over 4.0 per cent per day in Asia. It would double by 2020 if growth until then averaged 2.9 per cent per year. While accurate projections of coal consumption cannot be made for 2020, a review of economic and electricity growth rate projections and plans of the coal-consuming countries of Asia indicates that current plans are consistent with a doubling of coal consumption from 1995 levels by 2015 to 2025.

There is greater uncertainty about future coal consumption in the rest of the world. However, if the use of coal were to grow 1 percent per year in the rest of the world while growing 2.9 percent per year in Asia, global coal consumption would increase 60 percent, 1995-2020. The implications for GHG emissions are distressingly large.

Even though the projections suggested here are unlikely to be accurate, there is strong evidence that substantial growth in coal consumption and coal-related GHG emissions will take place over the 1995-2020 period under business-as-usual conditions. The GEF should consider whether it can and should use its scarce resources to try to change ongoing trends by promoting more climate-friendly coal technologies.

3. Trend in restrictions on coal emissions in developing countries.

Mounting scientific concern that GHG-induced climate change is a serious problem justifies considering energy scenarios with restrictions on GHG emissions related to fossil-fuel use in both industrialised and developing countries. But while there is increasing awareness and

concern about GHG emissions in many developing countries, the major coal-dependent developing countries have yet to take action to restrict coal use on a significant scale. In most developing countries, environmental activities relating to the coal industry and the coal-based power industry have been focussed instead on (a) coal technologies that can meet increasingly stringent environmental constraints on emissions of particulates, So_x and No_x, and (b) more energy efficient technologies that can improve the economics of coal conversion.

Major actions to reduce coal-related GHG in coal-dependent developing countries appear to be unlikely in the foreseeable future unless there is substantial financial and technical assistance from industrialised countries. Key to effective cooperation between developing and industrialised countries with regard to the coal and climate change challenge is the interest of the major coal-using developing countries in acquiring advanced coal technologies that increase energy conversion efficiencies, reduce local pollution problems, and provide fuel and product flexibility. But developing countries have had great difficulties in finding the financial support for projects that would help launch such technologies in the market. Industrialised country support for coal projects that serve these needs while simultaneously addressing the challenge of climate change could attract considerable interest in coal-dependent developing countries.

4. Risks to GEF's renewable energy portfolio

Concern was expressed at the workshop and also be an outside reviewer of the workshop report that if the GEF should launch a program relating to coal, the GEF renewable energy programs might suffer as a consequence.

From a technical perspective there is no "silver bullet" to deal with climate change. Renewables will be very important, as STAP has previously show (STAP, 1996), but it is also important to identify and pursue strategies for making fossil fuels more climate friendly.

The concern about the potential impact on GEF's renewables activities of a new coal initiative relates to the fact that the GEF has very limited resources. As STAP has shown (STAP, 1996), the characteristics of many renewable energy technologies are such that relatively modest resources of the scale that could be provided by GEF, appropriately targeted, could powerfully help launch the very embryonic renewable energy industries. In contrast, the world coal industry is large and coal projects tend to require much larger investments than do renewable energy projects. Only a few projects could potentially consume a significant share of GEF's resources available for addressing climate change.

On the other hand, because large investments in coal are routinely made by the private sector in the developing world, GEF might be able to apply judiciously some of its very limited resources to reorient investments relating to coal in ways that are more compatible with climate change concerns.

It may well be feasible and desirable for GEF to launch important new activities relating to coal without having to create first a new operational program relating to coal. As will be apparent from the discussion in this report (see especially Section 7), some of the most important coal-related activities needed in the near term to help put coal on a more climate friendly path could probably be pursued in the context of existing GEF operational programs

(e.g. Operational Program No. 5: Removal of Barriers to Energy Efficiency and Energy Conservation, Operational Program No. 7: Reducing the Long-Term Costs of Low Greenhouse Gas-Emitting Energy Technologies, and the embryonic operation program relating to transportation). Getting experience with coal activities this way would help ensure a proper balance between coal and renewable projects as GEF involves a coal strategy and understands better what its comparative advantage is in helping steer coal along a more climate-friendly path.

5. The importance of a systems approach to coal

Workshop deliberations and other considerations led STAP to conclude that the optimal technologies and strategies for reducing GHG emissions from coal are best identified using a systems approach. Besides the CO_2 emissions from coal combustion. CO_2 and other GHG emissions from other parts of the coal system should be taken into account in appropriate lifecycle analyses. GEF should look for opportunities to reduce GHG emissions throughout the entire chain of activities ranging from mining through end-use, for synergisms between different supply options [e.g. combined heat and power (CHP) instead of separate heat generation and electricity generation activities], for synergisms between coal and activities outside the coal industry [e.g. in the natural gas, oil, and chemical industries], and for synergisms between GHG mitigation goals and local environmental mitigation goals. Above all, the GEF should identify and develop a strategic perspective for reducing GHG emissions from coal to ensure that near term actions are consistent with and supportive of long-term goals.

6. GHG Emissions reduction strategies

In what follows, opportunities for reducing GHG emissions are discussed in three categories (i) near-term opportunities that could be adopted largely with existing technologies, (ii) options for reducing GHG emissions with advanced power-generating technologies, and (iii) a coal decarbonization/CO_2 sequestration strategy that would make feasible the achievement of deep reductions in emissions from the coal system.

6.1 Near-Term Opportunities

Near-term opportunities that could be adopted largely with existing technologies include (I) management reforms at existing coal power plants, (ii) retrofitting existing coal plants, (iii) confirming coal and biomass in coal plants, and (iv) coal bed methane recovery. These options could have significant and measurable impacts in reducing GHG emissions over the course of the next decade

6.1.1. Management Reforms at Existing Plants

A very low-cost near-term options for reducing coal-related CO_2 emissions is to introduce management techniques to improve the performance/efficiency of existing coal-fired power plants and large on-site generators (Siegel 1997). Industrialized country experience has shown that proper training, analytical techniques and audits applied to improving power plant performance can lead to increased plant availability, modest increases in thermodynamic efficiency and corresponding modest reductions in CO_2 emissions, while reducing overall

system costs. While the emissions reduction through management reforms is modest at any one plant, the reductions that could be achieved in a large number of plants in a relatively short period of time could be significant. An important advantage of these management techniques relating to climate change is that by making better use of existing capacity the need for new capacity is reduced, thereby buying time until new, more energy-efficient technologies are available.

Although commercially demonstrated, these techniques are not being widely used because of (I) a lack of understanding of the methodology involved, (ii) a mindset among utility managers that building new plant capacity is more important than modifying existing plants; (iii) a lack of case studies demonstrating the effectiveness of such programs; and (iv) the lack of an institutional framework conducive to such programs in many developing countries.

6.1.2 Retrofitting Existing Plants

Retrofitting existing boiler and power plant capacity with new, more modern equipment is often less costly than installing new capacity and can lead to improved efficiencies and reduced CO_2 emissions. A properly functioning market will enable this strategy in industrialized countries, but struggling businesses in developing economies do not have access to adequate capital to upgrade their facilities. Of course the demand for power is growing so rapidly in developing countries that the GHG emissions of existing plants are soon dwarfed by the emissions from new plants.

6.1.3 Cofiring Coal and Biomass

Cofiring of biomass (especially various biomass wastes) and coal in coal plants is a strategy offering multiple benefits (I) it leads directly to reduced GHG emissions as a coal substitute, (ii) until advanced biomass conversion technologies (e.g. integrated gasification/gas turbine of integrated gasification/fuel cell cycles) are commercially available cofiring biomass in large scale steam plants with coal will often lead to higher conversion efficiencies and more attractive economics than is possible with small biomass only steam plants; (iii) it is an effective way to use those biomass resources (e.g. some agricultural residues) that are available only part of the year and are difficult to store; and (iv) by creating market demand for biomass, cofiring helps create a biomass fuel infrastructure and thus helps pave the way to wider future use of biomass for energy. Biomass cofiring is most easily accommodated with fluidized bed combustion units.

6.1.4 Coal Bed Methane Recovery

Coal deposits contain methane that is released either during coal mining or through drilling into coal seems to recover the methane. Methane recovery during coal mining has been carried out for many decades to reduce the risks of mine explosions. Over the past decade there have been rapid advances in the commercial recovery of coal-bed methane (CBM) in industrialized countries (particularly the United States), however the commercial potential of CBM in developing countries has yet to be demonstrated on a large scale.

Estimates of world methane emissions from coal mining range from 35 to 60 billion cubic meters per year. Because methane is a powerful greenhouse gas, there is considerable interest

in CBM recovery in conjunction with coal mining as a climate change mitigation strategy. For example, the GEF is likely to undertake a demonstration project for CBM recovery and utilization in India as a potentially low-cost option for reducing GHG emissions.

CBM recovery should be considered as a GHG mitigation strategy from a much broader perspective than this, however, both because methane is the most climate friendly of the fossil fuels and because CBM resources are huge, especially deep CBM deposits associated with coals that will probably never be mined.

Emissions from methane combustion are only slightly more than half of the emissions from coal combustion per unit of energy contained in the feed stock. This climate benefit is amplified by the fact that typically methane can be utilized more efficiently than coal. Methane is also the cleanest of the fossil fuels, so that its use in place of coal provides substantial local environmental benefits as well.

Large amounts of methane are trapped in the pore spaces of some coals. Because coal is a microporous solid with large internal surface areas[1], it has the ability to sorb large amounts of gas and can hold much more gas than the same rock volume of a conventional natural gas reservoir of comparable size, at the same temperature and pressure. In general, gas content increases in increasing coal rank[2]. Moreover, for coal beds saturated with CBM, the gas concentration (in normal cubic meters per tonne of coal) increases with the reservoir pressure, and thus with the depth of the CBM deposit, by nearly 30% for each doubling of pressure or depth (Rice et al. 1993).

CBM resources are substantial. Worldwide, resources are estimated to be 85 to 260 trillion normal cubic meters (Rice et al. 1993), with an energy value of 3,400 to 14,000 EJ. For comparison, global remaining recoverable conventional natural gas resources are estimated to be in the range of 8,700 to 16,400 EJ, with a mean estimate of 11,800 EJ (Masters et al. 1994).

CBM currently accounts for 6% of total natural gas production in the U.S; only 3% of the CBM recovered is associated with coal mining, the rest is from deep unminable coal. For CBM recovery, current practice is to depressurize the reservoir by pumping water out, which leads to desorption of the gas from the micropores of the coal matrix, its diffusion through the coal matrix to macrofractures, and its flow through these macrofractures to the wellbore for recovery. The process is simple and effective but slow and inefficient, there is typically a significant time lag (days to months) between the beginning of the dewatering process and the time when substantial gas recovery rates are realized. However, a new CBM strategy involving CO_2 injection holds forth the promise of being considerably more efficient (see Section 6 3 2).

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[1] The internal surface area of these pore spaces amounts to ten to hundreds of square meters of per gram of coal

[2] Typically lignites contain very little gas, while higher-rank medium or low volatile bituminous coal semianthracite, or anthracite contain much more.

6.2 Advanced Power-Generating Technologies

There are several advanced coal technology options for increasing power plant efficiencies from the 30-35% levels that are typical of existing coal plants to the range 40-50% (HHV basis). Here attention is focussed on two sets of options: fluidized bed combustion and coal gasification based systems.

6.2.1 Fluidized Bed Combustion Technologies

In fluidized bed combustion, fuel is burned in a bed of fuel and other materials that behaves like a fluid, as a result of a gas passing upwards through the bed at a velocity sufficiently high for frictional drag to support the weight of the fuel and other particles but not so high as to transport the particles out of the bed. Typically only about 1% of the particles in the bed are active fuel particles, and bed temperatures of only 800 to 950°C are sufficient to burn practically any fuel, including various low-quality fuels. Atmospheric pressure fluidized bed combustion (AFBC) systems are well established in the market and pressurized fluidized bed combustion (PFBC) systems are commercially ready.

6.2.1.1 Atmospheric Pressure Fluidized Bed Combustion Systems

AFBC technology is commercially established with both bubbling and circulating fluidized bed configuration. AFBC technologies were first deployed in the late 1970s, mainly for steam and process heat requirements. Until the mid-1980s the dominant technology was the bubbling atmospheric fluidized bed combustor (BAFBC), with thermal capacities of about 10 MW_{th}. Since then most new AFBC capacity additions have involved circulating atmospheric fluidized bed combustion (CAFBC) systems, which account for about 70% of the 35 GW_{th} AFBC systems installed worldwide as of 1994.

Modest energy efficiency gains are feasible with a shift from pulverized coal with flue gas desulfurization to AFBC technology. AFBC technology is well-suited for CHP applications for capacities in the range 50 to 150 MW, (with CAFBC designs preferred to BAFBC designs, because of various environmental and operational advantages). AFBC technology also offers relatively simple strategies for dealing with air pollution constraints that are not especially demanding. However, use of AFBC systems can lead to significant GHG emissions in addition to the CO_2 emissions from coal burning - both from the use of large quantities of limestone or dolomite for SO_2 removal and from emissions of N_2O, a powerful greenhouse gas . In AFBC units SO_2 emissions can be reduced by adding limestone ($CaCO_3$) or dolomite [$CaMg(CO_3)_2$] to the bed. Sulfur is removed along with release of CO_2 according to the reaction.

$$CaCO_3 + SO_2 + 1/2\ O_2 \text{ ------------> } CaSO_4 + CO_2$$

Ideally, 1 mole of $CaCO_3$ is needed to remove 1 mole of SO_2. In practice, not all the limestone is effective in removing SO_2, so that extra limestone must be added to the bed to assure that a desired level of SO_2 removal is achieved. The extra limestone that does not react with SO_2 is typically calcined, according to

$$CaCO_3 \text{ ------------> } CaO + CO_2$$

thereby forming CaO ("quicklime"} and releasing additional CO_2 to the atmosphere. Up to 90% sulfur removal is practically realizable in AFBC units, typically with a Ca/S ratio in the bed = 2.0. The CO_2 emissions from limestone can be appreciable with relatively high sulfur coals. For example, when SO_2 emissions are reduced 90% and Ca/S = 2.0 in the bed, the CO_2 emissions from the limestone are equivalent to 7% of the CO_2 emissions from combustion, when burning Pittsburgh Seam Freeport coal with 2.6% sulfur.

Although conventional fossil fuel combustion technologies do not contribute significantly to N_2O emissions, atmospheric fluidized bed combustors do. N_2O is produced efficiently from fuel bound nitrogen at the low operating temperatures characteristic of AFBC, N_2O emissions can be the CO_2 equivalent of 5% to 20% of the CO_2 from combustion (Williams, 1997a). Lower rank coals (subbituminous and lignite) as a rule produce less N_2O than bituminous coals. Also, it is commonly found that CAFBC units produce more N_2O than BAFBC units, possibly because of the longer residence times for the former (de Soete, 1993). Reducing N_2O emissions from AFBC units will be technologically challenging and is a focus of ongoing research (Williams, 1997a).

6.2.1.2 Pressurized Fluidized Bed Combustion Systems

When a fluidized bed combustor is pressurized, it becomes possible to produce extra electricity by expanding the flue gases from the fluidized bed combustor through a gas turbine, thereby improving overall system efficiency, while reducing the boiler size. Pressurized fluidized bed combustion (PFBC) and the integrated gasification combined cycle (IGCC) are the leading competing advanced coal based power generating technologies. The principal advantage of PFBC technology in relation to IGCC technology is its simplicity, since it uses just one reactor (a combustor) compared to two (gasifier and combustor) for IGCC technology, which may give PFBC technology a near term cost advantage compared to IGCC technology. The current generation of PFBC technology is characterized by efficiencies in the range 37-40%. A major limitation of present PFBC technology is that unlike IGCC technology, it cannot take advantage of continuing advances in gas turbine technology. Future PFBC systems might be able to do this, but they will not have the simplicity that has been the major appeal of current PFBC designs. Several PFBC demonstration plants have been built (including a CHP plant with 135 MW of electrical capacity and a heat output capacity of 225 MW, owned by Stockholm Energy, at Vartan, Stockholm).

GHG emissions per kWh of electricity from combustion are lower for PFBC than for AFBC systems because of the higher thermodynamic efficiencies of PFBC units. Moreover, CO_2 emissions from the calcining to freelime of $CaCO_3$ present in the bed in excess of the stoichiometric amount needed for sulfur removal are suppressed in PFBC units at sufficiently high operating pressures (and thus high CO_2 partial pressure). Measured N_2O emissions at the PFBC CHP plant at Vartan, Sweden were the equivalent of about 10% of the CO_2 emissions from coal combustion (Dahl 1993; Williams 1997a). With advanced designs it may be feasible to suppress N_2O emissions with PFBC.

In any case, if either AFBC or PFBC is considered by the GEF as a candidate technology for reducing GHG emissions from coal, evaluation of the merit of the technology as a GHG-mitigation option must take into account, through appropriate lifecycle analysis, these potential GHG emissions in excess of emissions from coal burning, on a case-by-case basis.

6.2.2 Coal Gasification and Integrated Coal Gasification/Combined Cycle Technologies

Since the feasibility of firing combined cycle power plants with coal though the use of closely coupled oxygen-blown coal gasifiers was demonstrated in the 94 MW. Coolwater Project in Southern California, 1984-1989, there has been much progress in commercializing coal IGCC. This advanced coal technology can take advantage of the continuing improvements in gas turbine technology, making possible much higher efficiencies in power generation than is feasible with now mature steam-electric technology. Moreover, the key enabling technology, the oxygen-blown coal gasifier, has many other potential applications in the chemicals and fuels productions.

Local air pollutant emission levels for coal IGCC plants can be made as low as from natural gas combined cycle plants - far lower than for conventional steam-electric plants equipped with stack gas emission controls. Also, volumes of solid waste that must be disposed of are significantly less than for direct coal combustion systems (SFA Pacific 1993). Moreover, unlike the situation for FBC technologies, there are no significant GHG emissions other than from coal combustion.

In 1994 a 41% efficient 250 MW coal IGCC plant began operation in The Netherlands, in the late 1995, a 262 MW coal IGCC plant began operating in Indiana, in the United States, several other coal IGCC plants are expected to be operational soon in various parts of the world (Stambler, 1996). With advanced gas turbines, it is expected that coal IGCC efficiencies will be able to reach 50%. Since the average efficiency of coal-fired power plants in China in 1995 was about 29%, HHV basis [30%, LHV basis (Jiang, 1997)], a 50% efficient coal IGCC plant would emit less than 3/5 as much CO_2 per kWh as the average coal-fired power plant in China in 1995.

Although present day coal IGCC plants are not yet competitive in strictly economic terms with conventional coal steam-electric plants with flue gas desulfurization, near-term improvements in gas turbine technology might make coal IGCC plants fully competitive in many circumstances (Stoll and Todd, 1996). In the meantime, coal-rich developing countries intent on acquiring this technology can pursue near-term activities that would facilitate later introduction of coal IGCC technology for central-station power plants.

Consider that China is already using many modern coal gasifiers in the chemical process industries[3]. This activity might be extended to include the coproduction of towngas[4] along with chemicals (e.g. ammonia). One option would be to build a future ammonia plant with enough coal gasification capacity to accommodate both ammonia production needs and town gas for a nearby community. Since modern coal gasification technology is capital-intensive, it is highly desirable to maintain high capacity utilization of the gasifier equipment throughout the year. This might be achieved by producing methanol from the coal gas for rural applications (esp. For cooking) during periods when demand for town gas is low. A highly-

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[3] More than 20 Texaco gasifiers are operating under construction, or on order for the production of chemical fertilizer, methanol, town gas, and oxochemicals. In addition, about six Shell gasifiers and at least one Lurgi gasifier are being used to produce ammonia from coal.

[4] Towngas is currently supplied to about 40 million people in China.

efficient use of the town gas could be in small reciprocating engines for CHP applications in apartment buildings, commercial buildings, factories. Town-gas based CHP technologies are commercially available and highly energy-efficient compared to the separate production of electricity and heat, such CHP systems would be very cost-competitive today in markets where energy prices reflect full costs.

A very important and large market opportunity for coal IGCC technology is for CHP in the basic materials process industries (e.g. chemicals, pulp and paper, steel, petroleum refining), which have large baseload process heat requirements. For these applications coal IGCC technologies will be able to produce several times as much electricity per unit of process steam than can conventional steam-turbine technology (back-pressure steam-turbine CHP systems). Because electricity is worth much more than heat, CHP with coal IGCC can bring much more value to the producer than can CHP with steam-turbine technology. Rapidly industrializing countries represent ideal markets for such CHP systems because the basic materials processing industries are growing rapidly. These industries have the potential of becoming major providers of very cost-competitive and clean baseload power in these countries, if policies are in place that make competitive electricity prices available to these producers for the electricity they can make available to electricity grids.

Still another way to gain early experience with IGCC would be to gasify refinery residual oils (Stoll and Todd, 1996). In several ways, plant costs will often be lower for heavy oil gasification than for coal gasification. For example, solids handling, crushing, and feeding systems are not needed. Moreover, the generally lower levels of ash in heavy oils means less fouling of syngas coolers, so that lower cost designs might be employed. In addition, heavy "refinery bottom" oils tend to be cheap-sometimes even cheaper than coal on an equivalent energy basis. As a result, a heavy-oil integrated gasification/combined cycle power plant located, say, at a refinery, will often be able to produce electricity with today's technology at lower cost than a coal steam-electric plant. While this is only a niche market, it offers a basis for gaining experience with gasification technology relating to power generation before the technology is competitive for coal applications in central-station plants.

Even when such promising early market opportunities for coal gasification and IGCC technologies have been identified, there will be institutional barriers to their adoption. The barriers to the introduction of these advanced technologies vary from (I) energy prices distorted so far below market prices that it is difficult to adopt town gas and CHP strategies, (ii) regulatory policies that restrict the selling of power at market prices from onsite CHP systems to electric-grid systems, (iii) a lack of experience using these technologies in developing countries, (iv) industry reluctance to introduce new technologies with higher real or perceived risks, (v) banker reluctance to fund new technologies that may not be fully proven at commercial scales, (v) lack of enforcement of environmental regulations, which businesses to continue to use higher polluting coal-burning technologies, and (vi) institutional barriers within governments and international institutions many discourage the introduction of innovative new technologies.

6.3 A Coal Decarbonization/CO_2 Sequestration Strategy for Achieving Deep Reductions

An idea advanced at the workshop for using coal in the climate-friendly way is to separate

the energy value of the coal from its carbon content, by decarbonizing the coal to produce hydrogen and isolating from the atmosphere the CO_2 separated from the hydrogen at the production plant (Williams, 1997a). This option makes possible continued use of coal at substantial scale while reducing CO_2 emissions to the atmosphere to very low levels and simultaneously virtually eliminating local air pollutant emissions associated with conventional coal combustion technologies.

6.3.1 Producing Hydrogen from Coal

All the required technology for making hydrogen from coal is commercially available. The key enabling technology is modern oxygen blown coal gasification. This technology produces from coal "synthesis gas", a gaseous mixture consisting mainly of carbon monoxide and hydrogen, at high efficiency. The carbon monoxide in this synthesis gas is then reacted with steam in so-called "water-gas shift reactors", producing more hydrogen plus carbon dioxide. The net effect of gasification and shifting is thus to produce a gaseous mixture consisting mainly of hydrogen and CO_2. Various commercial technologies are available for separating the hydrogen (with up to 99.999% purity) from the CO_2 in the resulting gaseous mixture. For modern plants the hydrogen produced this way would have an energy content greater than 60% of the energy content of the coal from which it is derived (Williams et al. 1995; Williams, 1996), and the CO_2 separated from the hydrogen at the production plant would account for nearly all of the carbon in the original coal feedstock, CO_2 separation and sequestration in isolation from the atmosphere could be accomplished at a small increment to the cost of producing the hydrogen (Williams, 1996). This incremental cost could be reduced if sequestration of the separated CO_2 provided economic value, as will sometimes be the case (see Section 6.3.2). With sequestration of the CO_2 separated at the hydrogen production plant, the only CO_2 emissions associated with hydrogen production from coal arise from the production of external electricity and heat needed to make the hydrogen, which are modest even if these inputs are provided by burning coal (Williams, 1996).

6.3.2 Sequestering the Separated CO_2 in Coal-Rich Countries

There are various possibilities for sequestering the separated CO_2 in depleted oil and gas fields, deep saline aquifers, deep CBM reservoirs, and perhaps even the deep oceans. Although imperfectly understood, the capacity for underground sequestration might be adequate to hold securely hundreds and even thousands of gigatonnes of carbon as CO_2 (Socolow, 1997). For comparison, annual global CO_2 emissions from fossil fuel burning today amount to about 6 gigatonnes of carbon.

For coal-rich countries with deep coal resources (e.g. China, India, Botswana) a promising sequestration option is in CBM reservoirs that are so deep that mining the coal is impractical Injecting CO_2 into these coal beds might prove to be an economical strategy to recover from these coal beds methane for use as a fuel, leaving the CO_2 behind in the coal bed (Gunter et al. 1997)

As noted earlier (see Section 6.1.4), the current process for recovering deep CBM, though simple and effective, is slow and inefficient An alternative strategy that holds forth the prospect of being far more efficient is gas injection; for this purpose CO_2 is especially promising because it is twice as adsorbing on coal as methane; it can therefore efficiently

displace the methane adsorbed on the coal (Gunter et al. 1997). Carbon dioxide injection makes it possible to maintain reservoir pressure and produce methane gas quickly. As CO_2 moves through the reservoir it displaces methane, it has been found that very little of the injected CO_2 shows up in the production well until most of the methane has been produced. Thus the prospects for permanent sequestration of the injected CO_2 are good. Of course, sequestration of CO_2 in the coal bed would prevent subsequent mining of the coal. However, for much of the coal lying in deep beds that contain substantial quantities of CBM and that would be especially favorable sites for CO_2 sequestration, mining the coal would be too costly.

6.3.3 Marketing the Hydrogen and Byproduct CO_2

The key to making this overall strategy work is the existence of a market that places a high value on hydrogen. Although fuel markets for hydrogen do not yet exist, hydrogen is produced at significant levels throughout the world for chemical process applications, mostly at oil refineries and for ammonia production. For example, about 5% of natural gas produced in the United States is used to produce hydrogen for these applications. The ongoing trends to the use of heavier crude oils and to reformulated gasolines for meeting tightening air quality goals are leading to a growing demand for hydrogen at oil refineries, while growing populations are driving up the demand for ammonia for fertilizer. Because its conventional natural gas supplies are limited. China produces hydrogen as an intermediary in the production of ammonia and other chemicals from coal through coal gasification, as well as from natural gas.

When ammonia is produced from coal this way, a stream of byproduct CO_2 is generated. If the ammonia plant is associated with a plant for making urea for fertilizer from the ammonia (which is often the case), some of this byproduct CO_2 (0.5 moles of CO_2 per mole of ammonia) is used for urea manufacture. However, a comparable amount of excess CO_2 is generally also available. An alternative to venting the excess CO_2 is, for those ammonia plants that are sufficiently close to appropriate deep CBM deposits to sell it to companies that could use it to stimulate methane recovery from these deposits. Initially, the methane produced this way might be sold in a variety of natural gas markets. As market demand for hydrogen grows, the methane could be used as a feedstock for additional hydrogen production, with injection of the byproduct CO_2 into the deep coal beds to recovery additional methane (Williams, 1997c).

In the future hydrogen could also be marketed as a fuel. The prospects for wide use of hydrogen as a fuel are especially good if low-temperature fuel cells become well-established in transportation[5] and distributed CHP markets. Fuel cells are devices that convert the chemical energy in a fuel directly into electricity without first burning the fuel to produce heat, fuel cells can be much more energy-efficient in making electricity than conventional combustion-based technologies. The natural fuel for such fuel cells is hydrogen.

[5] The most promising option for storage of hydrogen onboard vehicles today is with light-weight, pressurized hydrogen storage canisters. In the future advanced concepts (e.g. high energy density carbon nanostructure storage technologies) might also be used for storage.

Low-temperature fuel cells might be supplied initially with a hydrocarbon fuels (natural gas or a liquid hydrocarbon fuel) that is converted at or near the point of use into a hydrogen-rich gas that fuel cells can use, this is the approach that will probably be followed in many industrialized countries. However, there would be strong internal market pressure to shift to hydrogen as soon a hydrogen infrastructure could be put into place, since these fuel cells "prefer" to be fueled by hydrogen that is produced centrally and distributed by pipelines to users (Williams, 1997b). Those developing countries that don't already have well-established hydrocarbon fuel infrastructure in place have the opportunity to"leapfrog" the already industrialized countries directly to a hydrogen economy.

At present, the two leading-candidate low-temperature fuel cells are the phosphoric acid fuel cell (PAFC) and the proton-exchange-membrane fuel cell (PEMFC). The PAFC is already commercially established for distributed combined heat and power (CHP) applications in apartment buildings and commercial buildings Typical commercial units produce electricity at a scale of 200 kilowatts, with the delivered fuel being natural gas that is "reformed" at the site to a hydrogen-rich mixture of gases that the fuel cell can use. Such fuel cells could also be used with hydrogen derived centrally for coal that is piped to distributed users.

The PEMFC offers the potential for much lower costs than the PAFC. Moreover, its much higher power density makes it an attractive candidate for use in transportation. Automotive applications of PEMFCs are a target of private and public sector R&D programs in Europe, North America, and Japan; several prototype PEMFC cars have already been built. Mass produced such fuel cells might become fully competitive with the internal combustion engine for vehicular applications (williams, 1997b). Initial applications of PEMFC's for automotive markets are targeted for the period 2005-2010. PEMFCs will be commercially available for distributed CHP and transit bus applications before 2000. PEMFCs would also be well-suited for applications in two and three-wheeled vehicles, trucks and locomotives.

Fuel cells operated on hydrogen derived from coal offer the potential for using coal at extraordinary high efficiency and with zero local pollutant emissions, without the need for pollution control technologies. The centralized hydrogen production plants themselves can be designed to be as clean as coal IGCC power plants, which can be as clean as natural-gas combined cycle power plants. Moreover, with centralized hydrogen production the separated CO_2 could be sequestered underground (e.g. in deep CBM reservoirs).

The high energy efficiency of fuel cells makes it possible to provide high levels of energy services from coal with relatively modest lifecycle CO_2 emissions, even without sequestration, as is illustrated with a thought experiment. Suppose that in China there will be 350 million fuel cell cars in 2050 (one for every 4.4 persons) driven on average 15,000 km a year and operated on coal derived hydrogen that is stored on board the cars as a compressed gas. Such cars would typically have a fuel economy of about 2.35 liters of gasoline equivalent per 100 km (100 miles per gallon of gasoline equivalent) (Ogden et al., 1997). The lifecycle CO_2 emissions from the hydrogen production system needed to support these cars would be about 180 million tonnes of C without sequestering the separated CO_2 or about 50 million tonnes of C with sequestration. For comparison total CO_2 emissions from burning of fossil fuels amounted to 720 million tonnes of C in 1990.

7. An evolutionary approach to achieving deep reductions in GHG emissions

Of the coal technologies reviewed here, the combination of coal decarbonization to produce hydrogen and CO_2 sequestration offers the greatest potential for using coal in a climate friendly way. The key enabling technology for decarbonization is modern coal gasification technology. For coal-rich countries, a key enabling option for sequestration is injection of CO_2 into deep beds of unminable coal to recover CBM as an energy source.

A coal use strategy that emphasizes these key enabling technologies so as to provide near term and mid term benefits would make it possible to evolve over the longer term to a coal economy based on hydrogen with sequestration of the separated CO_2.

The following is an exemplary set of near term (next 1-5 years), medium term (5-15 years) and long term (15+ years) actions that might make up such a strategy.

7.1 Near term measures

Discourage the use of those coal technologies that exacerbate GHG emissions as a means of encouraging gasification based technologies

> Examples of coal technologies that would exacerbate GHG emissions problems are some fluidized bed combustion technologies and direct coal liquefaction technologies. The problems with some fluidized bed combustion technologies have been noted (see Section 6.2.1). Direct coal liquefaction which involves producing a synthetic crude oil from coal that can be refined to produce traditional hydrocarbon fuels[6] than does the refining of petroleum crudes[7], for this reason the Energy R&D Panel of the President's Committee of Advisors on Science and Technology has recommended in its report to the President of the United Stats that R&D on direct coal liquefaction technology be eliminated from the US energy R&D program (PCAST Energy R&D Panel, 1997).

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[6] Alternatively, liquid fuels can be made from coal via indirect liquefaction, a process that begins with oxygen blown coal gasification to produce synthesis gas. With synthesis gas it is feasible to provide various clean liquid fuels (e.g. methanol and Fischer-Tropsch liquids), as well as hydrogen ammonia and a wide range of other chemicals In the coal R&D community of the industrialized world the focus of activity today is generally on indirect liquefaction instead of direct liquefaction, largely because the liquid fuels that can be produced via indirect liquefaction make it easier to address increasingly stringent local environmental concerns than is the case for liquid fuels derived from aromatic rich coal crudes. At present there is considerable global interest in making Fischer-Tropsch liquids from natural gas, as exemplified by the recent announcement by Exxon that it will build in Qatar a plant that will produce 100,000 barrels/day of Fischer-Tropsch liquids from natural gas. One of the major products that can be produced using the Fischer-Tropsch process is a clean synthetic middle distillate fuel (it contains zero sulfur and no aromatic) that is well suited for use in compression ignition, internal combustion engines

[7] In addition, it is difficult to make liquids derived from aromatic rich coal crudes as clean as is increasingly being required for liquids derived from petroleum crudes (e.g. to reduce to low levels the concentrations of the carcinogen benzene and other toxics) in order to address environmental health concern

Enact strict local air pollution regulatory measure in ways that would encourage the adoption of clean coal technologies such as modern gasification technologies.

Introduce gas price reforms that would facilitate the expanded use of town gas derived from coal as on alternative to home use of direct coal combustion where coal is so used today.

Enact policies that would facilitate the use of small reciprocating engines for CHP applications of this town gas at apartment buildings, commercial buildings and factories - including polices that make it possible for these power producers to sell electricity to the electric grid at market prices.

encourage the introduction of modern coal gasification technology for town gas production (e.g. as a coproduct at plants that produce ammonia using modern coal gasification technology).

Introduce integrated gasification/combined cycle (IGCC) technology in applications where is cost competitive today (e.g. using low cost residual refinery fuels) as a means of gaining experience with this technology and facilitating a transition to the use of IGCC technology with coal.

Carry out pilot investigations of methane recovery from deep (unminable) coal beds via CO_2 injection

> This should be done in collaboration with ongoing and planned investigation in North America for using CO_2 injection for recovery of methane from deep coal beds. One possible source of CO_2 might be at an existing plant that produces ammonia from coal. (In China some 25-35 million tonnes of coal are gassified annually to produce ammonia)

Carry out small scale demonstration projects involving the use of hydrogen fuel cells in transportation (for buses and two and three wheel vehicles) and for distributed CHP applications in apartment and commercial buildings

> The hydrogen used as fuel for these demonstrations could probably by excess supplies of hydrogen now produced for industrial applications (e.g. ammonia production) Where demonstrations are desired and such hydrogen supplied are not available, hydrogen derived electrolytically from off-peak hydroelectric power might be used instead.

7.2 Mid-Term Measures

Introduce IGCC technology for CHP applications in the energy intensive basic materials processing industries

Launch major projects involving methane recovery from deep (unminable) coal beds via CO_2 injection and sequestration.

> The recovery methane could be used in a wide range of natural gas applications including combined cycle power generation.

Carry out demonstration projects involving the use of fuel cells for "heavy-duty" transportation applications including locomotives[8].

For these applications consideration should be given to both hydrogen and methanol derived from coal as energy carriers delivered to vehicles.

7.3 Long-Term Measures

Commercialize hydrogen fuel cell technology in transportation markets, emphasizing buses, two and three wheel vehicles and locomotives.

Commercialize hydrogen fuel cell CHP systems for apartment and commercial building applications.

Produce hydrogen from CBM and from coal, with injection and sequestration of the separated CO_2 into CBM reservoirs for stimulating additional recovery of methane from coal beds.

This hydrogen would serve both industrial markets (e.g. ammonia production and petroleum refining) and the new hydrogen fuel markets.

8. Conclusions and recommendations

The STAP found because of the large and rapidly growing demand for coal particularly in Asia, the GEF should consider pursuing activities that could steer coal onto a more climate-friendly path, if this could be done in ways that do not detract from GEF activities aimed at helping launch various renewable energy technologies in the global energy market. It may well be feasible and desirable for GEF to launch important new activities relating to coal in the context of existing GEF operational programs. Getting experience with coal activities this way would help ensure a proper balance between coal and renewable projects as GEG evolves a coal strategy and understands better what is comparative advantage is in helping steer coal along a more climate friendly path.

In the GEF decides to launch a program relating to coal, it should be in the context of a strategic plan in which near term actions are consistent with and supportive of long term objectives. Moreover, the GEF should take a system approach to coal and seek to exploit many potential synergisms that offer multiple benefits in addition to reduced GHG emissions.

Among the options reviewed by STAP were very low cost actions that could be taken immediately, especially relating to the use of modern coal power plant management

[8] The electric drive [illegible] intensive transport systems For example, the railroads in China involve many steep grades, espe[illegible] China Steep grades require locomotives that can deliver high torque at low speeds. The best way to accomplish this is to use electric drive trains China has been expanding the use of electric locomotives in the west, with the needed electricity provided by external power lines But the shift to electricity is inhibited by the high capital costs of making adequate clearance for these lines in the many long tunnels in these mountainous regions, as well as by the temporary loss of needed rail capacity during periods of reconstruction Such problems could be avoided by use of fuel cell locomotives, which provide electric drives based on onboard power generation Fuel cells might make it possible to increase real capacity in China without expanding rail lines.

techniques, that would reduce costs while providing some GHG emissions abatement. Also more energy efficient power generating technologies could be helpful in reducing emissions, although care must be taken to ensure that on a lifecycle basis, emissions reduction achieved through energy efficiency improvements are not offset by GHG emissions other than from coal combustion, as might be the case for some fluidized bed combustion options.

STAP found that the option offering the greatest potential for using coal in a climate-friendly way is to separate the energy value of the coal from its carbon content, by decarbonizing the coal to produce hydrogen and by sequestering the CO_2 separated from the hydrogen at the production plant. While the widespread use of hydrogen as a fuel is not an imminent prospect, most of the technologies needed to embark on a coal decarbonization/CO_2 sequestration strategy are commercially available, and many activities that can be initiated today to facilitate a transition in the longer term to hydrogen could provide significant near term local environmental and economic benefits. The key enabling technology for decarbonization is modern coal gasification technology, which offers multiple local environmental and economic benefits as well as climate benefits. Key initial steps in the development of a coal strategy designed around modern coal gasification technology are energy pricing reforms, reforms that encourage the use of coal derived gas in combined heat and power applications, and effective local environmental policies. For coal rich countries a key option for sequestration is injection of CO_2 into deep beds of unminable coal to recover coal bed methane as an energy source, a strategy that offers multiple local environmental and economic benefits as well as multiple climate-change benefits. A key initial step is to explore the potential for enhanced methane recovery from deep coal beds using excess CO_2 at plants that produce ammonia from coal; CO_2 sequestration would be a "free byproduct" of such activity. Most of what should be done in the near term relating to both decarbonization and sequestration would be desirable even if there were no climate-change challenge.

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References

Dahl, Anders 1993. Operation Experience of the PFBC Plant in Vartan, Stockholm. Proceedings of the 1993. *International Conference on Fluidized Bed Combustion*, Volume 2, Lynn Rubow, ed. The American Society of Mechanical Engineers, San Diego, CA, 9-13 May.

de Soete, Nitrous oxide emissions from combustion and industry; chemistry, emissions, and control *Revue de L'Institut Francais du P_role,* **48** (4), July-August

Gunter, W D, T Gentzix, B A Rottenfusser, and R J H Richardson, 1997. Deep coalbed methane in Alberta, Canada a fuel resource with the potential of zero greenhouse emissions. *Energy Convers Mgmt*, **38** (Suppl.) pp. S217-S222.

Jiang Zhesheng, 1997. Prospects for clean power generation technology in China. *Proceedings of the APEC Fourth Technical Seminar on Clean Fossil Energy, Beijing*, The People's Republic of China, 7-9 October 1996.

Masters, C D, E D Attanasi, and D H Rool, 1994: World petroleum assessment and analysis. *Proceedings of the 14th World Petroleum Congress.* Stavanger, Norway.

Ogden, J M Steinbugler, and T Kreutz, 1997: Hydrogen as a fuel for fuel cell vehicles: a technical and economic comparison. Presented at the 8th Annual Conference of the National Hydrogen Association, Arlington, VA, 11-13 March.

PCAST Energy R&D Panel, 1997. Federal Energy Research and Development for the Challenges of the Twenty-First Century. Panel on Federal Energy R&D of the President's Committee of Advisors on Science and Technology, 1 October 1997.

Rice, D D, B E Law, and J L Clayton, 1993. Coal-bed gas an undeveloped resource. *In The Future of Energy Gases.* U S Geological Survey Professional Paper No 1570. United States Government Printing Office, Washington, DC, pp. 389-404.

SFA Pacific, 1993. Coal gasification guidebook status, applications, and technologies. Final Report EPRI TR-102034 prepared for the Gasification Power Plants Program, Generation & Storage Division, Electric Power Research Institute, Palo Alto, CA, December.

Siegal J, 1997. Economic and Environmental Benefits of Improving the Performance of Coal-Fired Power Stations, viewgraphs presented at the STAP Workshops on Options for Improving Coal Supply Systems to Reduce Greenhouse Gas Emissions, Amsterdam, 16-17 June 1997.

Socolow R H, ed, 1997. Fuels Decarbonization and Carbon Sequestration: Report of a Workshop, PU/CEES Report No 302. Center for Energy and Environmental Studies, Princeton University, Princeton, NJ.

Stambler I, 1996. Progress in IGCC and advanced cycles outlined at EPRI meeting. *Gas Turbine World*. 26(1) 16-23.

STAP (Scientific and Technical Advisory Panel), 1996: Outlook for Renewable Energy Technologies, Strategic Considerations Relating to the GEF Portfolio and Priorities for Targeted Research. Report prepared by the Scientific and Technical Advisory Panel of the Global Environment Facility, Nairobi, Kenya, September.

Stoll H, and D M Todd, 1996. Competitive power generation costs for IGCC. Paper presented at the EPRI Gasification Technologies Conference. San Francisco, CA, 2-4 October.

Williams, R H, E D Larson, R E Katofsky and J Chen, 1995. Methanol and hydrogen from biomass for transportation. *Energy for Sustainable Development* 1 (5), 18-34. See also Williams, R H, E D Larson, R E Katofsky and J Chen, 1995. *Methanol and Hydrogen from Biomass for Transportation with Comparisons to Methanol and Hydrogen from Natural Gas and Coal*. PU/CEES Report No 292, Center for Energy and Environmental Studies, Princeton University, Princeton, NJ, July.

Williams, R H, 1997a. An Advanced Technology Strategy for Using Coal in a Greenhouse Constrained World, paper presented at the STAP Workshop on Options for Improving Coal Supply Systems to Reduce Greenhouse Gas Emissions. Amsterdam, 16-17 June 1997.

Williams R H 1997b. Successful Commercialization of Fuel Cars as a Driver for Hydrogen Infrastructure Development, paper presented at the Workshop on Technological Opportunities for Fuels Decarbonization and Carbon Sequestration, Washington, DC 28-29 July 1997.

Williams R H, 1997c. Hydrogen Production from Coal Bed Methane (CBM) Using Byproduct CO_2 for Sequestration in the Coal Bed. Draft manuscript Center for Energy and Environmental Studies, Princeton University, Princeton, NJ, USA, 27 June.

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FUEL CELLS, COAL, AND CHINA

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ABSTRACT

Rapid advances are being made in proton exchange membrane (PEM) fuel cell technology. This fuel cell generates electricity and low-temperature byproduct heat with zero or near-zero local air pollutant emissions, without the need for complicated end-of-pipe control technologies. PEM fuel cell technology will enter some commercial markets by the year 2000. There are good prospects that in mass production and with appropriate fuel infrastructure in place, PEM fuel cells could be fully competitive with conventional energy technologies in a wide range of transportation and stationary combined heat and power (CHP) applications.

The PEM fuel cell "prefers" to be fueled by hydrogen (H_2), which can be manufactured from most carbonaceous feedstocks using commercial technology. The adoption and wide use of PEM fuel cells by China would make possible clean use of its abundant coal and coal bed methane (CBM) resources for the production of the needed H_2. A new approach for making H_2 from these feedstocks that involves injecting the byproduct CO_2 into beds of deep unminable coal to stimulate the recovery of CBM from these coal beds makes it possible to provide the needed H_2 not only with low local and regional air pollutant emissions but with low lifecycle CO_2 emissions as well, since the injected CO_2 would remain sequestered in the coal beds.

Rapid growth in demand for transportation services from the present very low base level suggests an urgency for getting underway a transition to fuel cells in China, at least in the transport sector—in light of the scarcity of China's domestic oil resources and the prospect that world oil prices might be rising by the time oil begins to play a significant role in its energy economy, if China were to pursue an oil-intensive transportation strategy.

On the demand side, a transition to fuel cells might begin with commercial demonstration projects relating to the most important prospective fuel cell markets in China. Such demonstration projects should include both CHP and transportation applications, with emphasis on the latter, in light of the "window of opportunity" for leapfrogging over internal combustion engines to fuel cells in the transportation sector. Transportation demonstration projects should include urban buses (for which a demonstration project is already being planned in China), 2- and 3-wheel vehicles, locomotives, and trucks—important transport modes in China that are getting little attention in the industrialized countries, where attention is focused on the automobile.

Because it is already making H_2 from coal (using modern coal gasification technology) in the manufacture of ammonia for fertilizer applications, China does not have to acquire new technology from abroad to create an industry for producing H_2 for fuel cells. Moreover, China could launch a H_2 production industry based on coal plus CBM even before fuel cells are commercially ready, by siting plants for ammonia manufacture from coal near methane-rich deep coal reservoirs. The CO_2 byproduct of H_2 manufacture could be used to stimulate CBM recovery from these deep coal beds. The recovered CBM could be used either to make more H_2 for ammonia manufacture or to make electricity in combined cycle power plants. In either case there are good prospects that the H_2 or electricity produced from this CBM would be competitive with H_2 or electricity made from coal, while generating "negative" CO_2 emissions (because about two kmols of CO_2 would be sequestered in the coal bed for each kmol of CBM recovered).

INTRODUCTION

Low-temperature fuel cells, especially proton-exchange membrane (PEM) fuel cells, offer the potential for meeting energy needs in both transportation and stationary combined heat and power (CHP) applications:

- using a variety of carbonaceous feedstocks to provide the needed hydrogen (H_2) or a hydrogen-rich energy carrier that is readily usable by such fuel cells, while

- generating zero or near-zero local air pollutant emissions without the need for complicated end-of-pipe control technologies, and

- making it possible to provide energy services from fossil fuels with low levels of greenhouse gas emissions.

Progress has been rapid in bringing PEM fuel cell technology closer to commercialization (Dunnison and Wilson, 1994, Kircher et al., 1994; Little, 1995; Mark et al., 1994; Prater, 1996), even for fuel cell cars (see Box A), an especially daunting application, in light of the high fuel cell power density requirements and the low costs that must be realized in order for fuel cells to compete with internal combustion engines. Yet even for cars there are good prospects that in mass production and with appropriate fuel infrastructure in place, PEM fuel cells could also be competitive with conventional energy technologies (Williams, 1993; 1994).

Although H_2 is the fuel of choice for use in PEM fuel cells, a H_2 fuel infrastructure is not yet in place anywhere in the world. Accordingly, for many applications PEM fuel cells will be introduced into the market using existing hydrocarbon (HC) fuel infrastructures, with conversion of the HC fuel into a H_2-rich gas suitable for fuel cell use at the point of use–e.g., onsite reforming of natural gas for CHP applications and processing by partial oxidation of gasoline onboard a car (Mitchell et al., 1995), a strategy being pursued by one U.S. automaker (see Box A). Use of fuels other than H_2 is likely to be only a transitional strategy for launching low-temperature fuel cell technologies in the market, however. It has been shown in the case of the automobile, for example, that if the fuel cell car is successfully launched in the market with a liquid HC fuel, the automotive system would generate internal market pressures to shift to H_2 as soon as the H_2 infrastructure could be put into place, as a result of the higher first cost, higher maintenance cost, and lower fuel economy[1] of the gasoline fuel cell car relative to the H_2 fuel cell car (Williams, 1997).

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[1] The lower fuel economy arises in large part because the PEM fuel cell operates at such a low temperature (~ 80 °C) that little if any of the fuel cell's "waste heat" can be used for fuel processing; as a result, point-of-use fuel processing to produce a H_2-rich gas suitable for fuel cell use is relatively inefficient, in contrast to the situation with high-temperature fuel cells.

Box A: Progress in Developing Motor Vehicles Powered by PEM Fuel Cells

1993	Clinton Administration announces Partnership for a New Generation of Vehicles (PNGV) with U.S. automakers, aimed at introducing by 2004 production-ready prototypes of "cars of the future" that will be three times as fuel efficient as today's cars but will maintain size and performance and cost no more to own and drive
1993	Ballard Power Systems of Vancouver (Canada) introduces proof-of-concept H_2 PEM fuel cell bus (with compressed H_2 storage)
1995	Daimler-Benz introduces NECAR I, a H_2 PEM fuel cell test van (with compressed H storage, Ballard fuel cell)
1995	Ballard demonstrates H_2 PEM fuel cell bus suitable for commercial use (with compressed H_2 storage)
1995	Mazda demonstrates a H_2 PEM fuel cell golf cart (with compressed H_2 storage)
1996	Daimler-Benz introduces NECAR II, a prototype passenger van equipped with a compact H_2–powered fuel cell system (power density of 1 kW_e/liter, 0.7 kW_e/kg for the fuel cell stack) developed jointly with Ballard (with compressed H_2 storage)
1996	Toyota introduces prototype PEM H_2 fuel cell car (with metal hydride storage)
1996-97	Ballard sells several H_2 PEM fuel cell buses to cities of Chicago and Vancouver
1997	Ballard and Daimler-Benz form joint venture with $320 million planned investment to develop PEM fuel cell cars, with commercialization targeted for 2005 timeframe
1997	Daimler-Benz introduces NECAR III, a prototype small fuel cell passenger car [with onboard methanol (MeOH) reformer]
1997	Toyota introduces prototype fuel cell passenger car (with onboard MeOH reformer)
1997	Ford joins Daimler-Benz & Ballard in joint venture to commercialize fuel cell cars, bringing planned pooled investment total to $420 million; fuel cell power trains for cars targeted for commercialization in 2004
1998	GM announces it will develop production-ready prototype fuel cell cars by 2004
1998	Chrysler announces it will develop production-ready prototype fuel cell cars by 2004 (with onboard gasoline partial oxidation systems)
1998	Mobil Corporation and Ford Motor Company form a strategic alliance to develop a hydrocarbon fuel processor for use in fuel cell vehicles

This paper discusses why an accelerated fuel cell development strategy is an attractive option for China and how such a strategy might be initiated with both fuel cell demonstration projects for transportation and stationary CHP applications and a H_2 production strategy rooted in China's fertilizer industry.

RATIONALE FOR RAPID INTRODUCTION OF LOW-TEMPERATURE FUEL CELLS IN CHINA

The low-temperature fuel cell offers China the opportunity to deal effectively and simultaneously with multiple challenges posed by the energy sector by making it possible to:

- avoid large increases in oil imports to support its rapidly growing transportation energy needs by providing coal-derived H_2 for fuel cell applications in transportation,
- avoid developing a large liquid HC fuel infrastructure for transportation and leapfrog directly to a transport fuel infrastructure using H_2, the preferred fuel for low-temperature fuel cells,
- provide energy services for both transportation and stationary CHP applications with little or no air pollution and without the need for costly "end-of-pipe" pollution control equipment and supporting regulatory/maintenance infrastructures, and
- greatly reduce CO_2 emissions both as a result of the increased efficiency of providing energy services with fuel cells and from the fact that the CO_2 produced as a byproduct of H_2 production from coal can be readily isolated from the atmosphere in many instances.

Perhaps most important is the prospect that the adoption and wide use of low-temperature fuel cells would make it possible for China to use its abundant coal resources for the production of a high-value energy carrier in ways that would involve low local, regional, and global environmental impacts, at costs that would be competitive with costs for conventional energy technologies.

Avoiding Large Increases in Oil Imports

By rapidly introducing fuel cells powered by fuels derived from coal, China could avoid becoming a major oil importer.

Today China uses very little oil. In 1990 oil was used at a rate of 2.3 million barrels per day or ¼ of a barrel per capita per year (13% of total primary energy use), compared to 17 million barrels per day or 25 barrels per capita per year (41% of total primary energy consumption) for the United States. China's 1.25 billion people (24% of world population) accounted for only 3.6% of global oil use in 1990.

Unless a shift away from oil is brought about quickly, however, China will not be able to avoid large increases in oil imports, because of the rapid pace of change and China's limited domestic oil resources. Oil use in China grew at an average rate of 7.5%/year, 1990-1996.

China became a net oil importer in 1993, and by 1996 imports accounted for 12% of China's oil consumption (EIA, 1998). Under a business-as-usual energy future, oil use is projected to expand approximately 4-fold, 1990-2020, to about 9 million barrels of crude oil per day by 2020 (Li et al., 1995). Projected cumulative oil consumption during the period 1990-2020 (Li et al., 1995) is equivalent to about 150% of China's identified oil reserves and 80% of its estimated total ultimately recoverable conventional oil resources (identified reserves plus estimated undiscovered resources), as estimated by the U.S. Geological Survey (Masters et al., 1994).

Although there is no danger that the world will run out of oil in the foreseeable future, low cost oil supplies many well be in relatively limited supply. It can be expected that oil prices will rise, once world production of conventional oil has peaked. The timing of this peak is uncertain. The Shell International Petroleum Company expects oil production to peak sometime in the period 2020-2030 (Kassler, 1994; Shell, 1995). Some oil geologists expect production to peak in less than a decade (Campbell and Laherrere, 1998). In either case, oil prices are likely to be rising just as China begins to become a major oil consumer, as projected for a business-as-usual energy future.

Leapfrogging to Hydrogen in Transportation

The pervasiveness of the liquid HC fuel infrastructure for transportation in the industrialized world impells an industrialized country strategy for making a transition to fuel cells in transportation that initially involves processing such fuels onboard vehicles into a H_2-rich gas that fuel cells can use, before making a transition to H_2 fuel, even though the latter is likely to be economically preferable if H_2 were readily available (Williams, 1997).

In contrast, both the road transportation system and the supporting liquid HC fuel infrastructure are at low levels of development in China. In 1991 China had only 1 road vehicle for every 190 people, compared to an average of 1 for every 9 people in the world, 1 for 3 people in Europe, and 1 per person for the United States (WRI, 1994), and the privately owned automobile is practically non-existent in China.[2] Moreover, transportation accounted for only ¼ of China's total oil consumption in 1990 (compared to 2/3 in the United States), and the private car accounted for less than 1% of oil used in transportation. (For comparison, light-duty vehicles account for nearly 3/5 of transportation oil use in the United States.)

Because its liquid HC fuel infrastructure for transportation is not yet well developed, China has a "window of opportunity" for introducing a H_2 fuel infrastructure for fuel cells in transportation, avoiding the intermediary step of first introducing the more costly liquid HC fuel-based fuel cell technology, if the introduction of fuel cell vehicles could be accomplished quickly.

But this situation is changing rapidly and the window of opportunity will not remain open for long. Between 1982 and 1992, freight traffic (in tonne-km) increased 8.4%/year, while highway freight traffic increased 14.7%/year, with its share of freight traffic increasing during this period from 7.3% to 12.9%. During this same period, public passenger traffic (in passenger-

2 There were only 230,000 private cars in use in China in 1990 (Li et al., 1995).

km) increased 9.7%/year, while highway passenger traffic increased 12.7%/year, with its share of passenger traffic increasing during this period from 35.1% to 45.9% (SSB, 1993). Looking to the future, freight and public passenger traffic volumes are projected to increase 3.3-fold and 4.4-fold, respectively, and the number of private cars is projected to increase to 40 million by 2020 (Li et al., 1995). Energy use in the transport sector of China is projected to grow at an average rate of 5.7%/year, 1990-2020, during which period the transport sector's share of China's primary energy consumption is expected to grow from 6.8% to 10.6% (Li et al., 1995).

Meeting Air Quality Goals without Cumbersome Regulatory Infrastructures

People in some large cities in China are already suffering from heavily polluted air, mainly as a result of SO_2 and particulate emissions from stationary coal-burning sources—see Figure 1. The expected rapid growth in road transportation energy use would greatly exacerbate this situation, if this buildup were based on conventional petroleum-powered internal combustion engine technology and not accompanied by the adoption of stringent emission control technologies.

Unfortunately, the prospects for meeting air quality goals by mandating the use end-of-pipe controls on such fossil fuel-using equipment are not bright. In China, as in most other developing countries as well, the environmental regulatory system needed for ensuring compliance with air quality regulations is relatively weak, and the needed supporting maintenance infrastructure is practically non-existent. Not only would considerable time be required to build up the needed infrastructures, but also mandating the use of end-of-pipe controls on energy systems originally designed without environmental concerns in mind has proved to be far less effective than is intended, even in countries with well-developed pollution control infrastructures. In the United States, for example, lifecycle emissions of criteria air pollutants from automobiles have proved to be far greater than the mandated standards (see Figure 2)—largely because many cars are not driven in the manner prescribed in the driving cycle specified in the regulation, and because much of the pollution burden is due to the modest fraction of cars that are poorly maintained.

If H_2 fuel cells instead of liquid HC-fueled internal combustion engines were to become the norm for the transportation system in China, air quality goals could be met without the need for end-of-pipe control technologies and the accompanying far-reaching regulatory and maintenance infrastructures.

Using Coal with Low Greenhouse Gas Emissions

The adoption of fuel cells for transportation and stationary CHP applications would give China the opportunity to use its vast coal resources with low levels of greenhouse gas emissions, both because of the high efficiency of H_2 fuel cell systems relative to conventional energy systems and the good prospects for isolating from the atmosphere the CO_2 separated from H_2 at H_2 production plants.

Consider transport applications of fuel cell vehicles powered with H_2 derived from coal. Although such fuel cell vehicles emit no CO_2 in their operation, large quantities of CO_2 are

generated in the manufacture of H_2. When H_2 is made from coal the lifecycle CO_2 generation rate associated with its manufacture, per unit of H_2 energy produced, is about 1.8 times the lifecycle emission rate associated with the production and consumption of the energy-equivalent amount of gasoline derived from crude oil (Williams, 1996). However, H_2 fuel cell vehicles would tend to be two to three times as energy-efficient as conventional gasoline internal combustion engine vehicles of comparable performance. For example, a H_2 fuel cell car is expected to be 2.5 times as energy-efficient as a gasoline internal combustion engine car of comparable size and performance (Ogden et al., 1997), so that lifecycle CO_2 emissions per km would be less than ¾ of the lifecycle emissions for the gasoline car, if the CO_2 separated from the H_2 at the fuel processing plant were vented to the atmosphere.

Much deeper reductions of the CO_2 emissions could be realized if the CO_2 separated from the H_2 at the production facility (which can be provided in a relatively pure stream that contains most of the carbon in the original coal) were stored in isolation from the atmosphere. There is growing evidence that this might be practically achievable at large scale. In the scientific community there is increasing confidence in the notion that sequestration of a significant fraction of the next several centuries of global CO_2 production from the use of fossil fuels may be feasible, especially in light of new understanding of the potential for sequestration in geological reservoirs—depleted oil and gas fields, deep saline aquifers, and deep beds of unminable coal (see Appendix).

CO_2 sequestration is a particularly attractive option when CO_2 is made available for sequestration at low cost, as would often be the case if CO_2 were produced as a byproduct of H_2 production from coal or other fossil fuels (Williams, 1996). A low CO_2-emitting strategy for using fossil fuels in the future would be to produce H_2 in centralized facilities for distributed low-temperature fuel cell applications, with sequestration of the separated CO_2 (see Figure 3). At worst the cost of CO_2 sequestration would add only marginally to the cost of the produced H_2 (Williams, 1996); the cost of sequestration can be zero or even "negative" at some sites where there are markets for the byproduct CO_2 as well as the H_2.

One possible market for byproduct CO_2 is for enhanced oil recovery; CO_2 injection into oil reservoirs for tertiary oil recovery is commercially well-established technology (Blunt et al., 1993). Another potential market that could prove to be especially important for China would be to inject CO_2 into deep coal beds to stimulate the recovery of methane from such coal beds, as discussed below.

FRAMING A FUEL CELL ENERGY DEVELOPMENT STRATEGY IN THE CONTEXT OF CHINA'S NEEDS AND ENERGY RESOURCE ENDOWMENTS

Fuel Cells in Relation to China's Transport Needs

China's specific transport technology needs are also especially well suited for early adoption of fuel cell technology. Although the automobile is the focus on fuel cell technology development efforts for transportation in the United States, Europe, and Japan (see Box A), the passenger bus, the primary means of motorized passenger transport in urban areas of China, will be the first transportation market in which fuel cells will be used. Ballard Power Systems has

Box B: Fuel Cells for Chinese Locomotives?

The electric drive trains and onboard electricity generation offered by fuel cells are especially appealing for mountainous railroad-intensive transport systems. For example, the railroads in China involve many steep grades, especially in mountainous regions in western China. Steep grades require locomotives that can deliver high torque at low speeds. The best way to accomplish this is to use electric-drive trains. China has been expanding the use of electric locomotives in the west, with the needed electricity provided by external power lines. But the shift to electricity is inhibited by the high capital costs of making adequate clearance for these lines in the many long tunnels in these mountainous regions, as well as by the temporary loss of needed rail capacity during periods of reconstruction. Such problems could be avoided by use of fuel cell locomotives, which provide electric drives based on onboard power generation. Fuel cells might make it possible to increase rail capacity in China without expanding rail lines.

already sold several H_2 PEM fuel cell buses to the cities of Chicago and Vancouver (Canada) and will soon be producing fuel cell buses commercially. Moreover, 2- and 3-wheeled vehicles (e.g., mopeds,[3] tuk-tuks), trucks, and even locomotives (see Box B) are also likely to be potentially important early markets for fuel cells in China, and all of these markets are likely to be more easily developed than the automotive market, which will probably require meeting much lower cost targets in order to make the fuel cell competitive.

The Chinese government is already actively exploring the prospects for introducing fuel cell buses in China, to follow up the findings of a pre-feasibility study (which included a study tour by Chinese experts to fuel cell and fuel cell bus development sites in North America and Europe) supported by the United Nations Development Programme. The State Science and Technology Commission (SSTC) of China is presently preparing a call for tender (expected, at the time of this writing, to be issued shortly) for a fuel cell bus demonstration project, to be carried out with the Beijing Public Transportation Company (a bus company). The demonstration is to involve operating for a year with passengers on the streets of Beijing one or two fuel cell buses. If the demonstration project is successful, it will be followed up with a joint venture between the participating foreign fuel cell company, the Beijing Public Transportation Company, and possibly other appropriate Chinese companies, to commercialize and manufacture fuel cell buses in China.

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3 Liquid HC-fueled mopeds and other two-stroke engine vehicles are already major contributors to local air pollution in some Chinese cities and targets of aggressive regulatory initiatives. For example, Shanghai intends to replace 80% of its fleet of 470,000 gasoline-powered mopeds with battery-powered electric mopeds by the year 2000 because of air pollution concerns.

Just as there is a growing consensus that fuel cell cars are likely to be less costly to own and operate than battery-powered electric cars, H_2 fuel cell mopeds (e.g., mopeds powered with H_2 stored in small canisters of compressed H_2 or in metal hydride storage units) might prove to be more economically attractive than battery-powered mopeds. Studies to test this hypothesis are warranted.

Roles for Coal in Fueling Fuel Cells

If China should adopt H_2 low-temperature fuel cell technology for transportation and stationary CHP applications, it would probably give close consideration to using coal as a feedstock for making the needed H_2.

Making H_2 from coal would not require China to acquire new technology from abroad. Rather China would have to adapt to energy applications technology that is already well established in China in the chemical process industry, mainly for the manufacture of ammonia (NH_3), a process in which the production of H_2 is an intermediary product. The key enabling technology is coal gasification.[4] Because of the scarcity of its conventional natural gas resources, 70% of China's NH_3 production in 1990 was based on the gasification of some 37 million tonnes of coal (Li et al., 1990). Moreover, China is rapidly building up a capacity to make fertilizer from coal using modern coal gasification technology. China already has in operation, under construction, or on order, 25-30 modern, oxygen-blown coal gasifiers, all for applications in the chemical process industries, mostly for ammonia production.[5] Chinese interest in such technology arises both as a result of the expected continuing increase in the demand for nitrogen fertilizer[6] and because much of the existing coal-based NH_3 production is based on the use of small, inefficient, and polluting plants,[7] many of which are likely to be replaced with larger, cleaner, and more cost-competitive plants.

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[4] NH_3 is produced via the Haber process by combining (at a pressure in the range 130 to 680 atmospheres) nitrogen (N_2) and H_2 in the presence of an appropriate catalyst, according to:

$$N_2 + 3H_2 \rightarrow 2NH_3.$$

NH_3 can be made from coal, producing the needed H_2 via oxygen-blown coal gasification. Both the oxygen (O_2) needed for coal gasification and the N_2 needed for the Haber process can be obtained by air liquefaction. The oxygen-blown gasifier produces from coal at high efficiency "synthesis gas," a gaseous mixture consisting mainly of carbon monoxide (CO) and H_2. The CO in this synthesis gas is then reacted with steam in so-called "water-gas shift reactors," producing more H_2 plus CO_2. The net effect of gasification and shifting is thus to produce a gaseous mixture consisting mainly of H_2 and CO_2. Various commercial technologies are available for separating the H_2 (with up to 99.999% purity) from the CO_2 in the resulting gaseous mixture. For modern plants the H_2 produced this way would have an energy content (on a higher heating value basis) greater than 60% of the energy content of the coal from which it is derived (Williams et al., 1995a; 1995b).

[5] More than 20 Texaco gasifiers are operating, under construction, or on order for the production of chemical fertilizer, methanol, town gas, and oxochemicals. In addition, about six Shell gasifiers and at least one Lurgi gasifier are being used to produce ammonia from coal.

[6] The production of NH_3 is projected to increase from 22.5 million tonnes in 1990 to 37.8 million tonnes in 2020 (Li et al., 1995). Fertilizer demand is not expected to grow more rapidly than this because China already uses fertilizer at a high rate—some 148 kg/hectare/year, compared to a world average of 54 kg/hectare/year.

[7] In 1990 18.7% of total NH_3 production in China was accounted for by large, relatively efficient plants that use natural gas or oil as feedstocks; most of the rest of the ammonia production was accounted for by much less efficient medium-scale and small-scale plants that use coal (Li et al., 1995).

As discussed below, there is an near-term opportunity for beginning to build up an industrial capacity in China for producing H_2 with low lifecycle CO_2 emissions: (*i*) by using the CO_2 produced as a byproduct of the manufacture of NH_3 from coal to stimulate the recovery of methane from deep unminable coal beds, and (*ii*) by using the CBM recovered this way to produce extra H_2 to produce more NH_3 and the CO_2 byproduct of making H_2 from CBM to stimulate the production of still more CBM. This opportunity arises both because the manufacture of NH_3 from coal provides a significant source of low-cost CO_2 that might be used for CBM recovery and because China has some of the largest CBM resources in the world.

CBM RESOURCES AND CURRENT CBM RECOVERY TECHNOLOGY

Coal beds are both source rocks and reservoir rocks for large quantities of methane-rich gas. This gas is typically produced at rates ranging from 150 to 200 normal cubic meters (Nm^3) per tonne of coal throughout the burial history of the coal as a result of biogenic and thermogenic processes whereby plant material is progressively converted to coal (Rice et al., 1993). Large amounts of methane produced this way will remained trapped in the coal bed, adsorbed on coal surfaces. Because coal is a microporous solid with large internal surface areas (tens to hundreds of square meters of per gram of coal!), it has the ability to adsorb large amounts of gas and can hold up to five times as much gas as a comparable conventional natural gas reservoir of comparable size, at the same temperature and pressure (Gunter et al., 1997). In general, gas content increases with increasing coal rank; typically lignites contain very little gas, while high-rank coals (e.g., medium- or low-volatile bituminous coals, semianthracite, or anthracite) can contain as much as 30 Nm^3/tonne. For medium-volatile or higher ranks, the coals may have generated more methane than they can store, resulting in the expulsion of the excess methane into adjacent reservoirs (e.g., trapped under a caprock above the coal bed).

CBM resources are substantial. Worldwide CBM resources are estimated to be 85 to 262 trillion Nm^3 (Rice et al., 1993); the corresponding energy value is 3,400 to 10,400 EJ (assuming the gas is entirely CH_4 with a HHV of 39.72 MJ/Nm^3), equivalent to 0.3 to 0.9 times the mean estimate of remaining recoverable conventional natural gas resources worldwide (Masters et al., 1994). In China, CBM resources are estimated to be 30 to 35 trillion Nm^3 (Rice et al., 1993); the corresponding energy value is 1,190 to 1,390 EJ; for comparison, the mean estimate of the remaining recoverable conventional natural gas resources in the United States is 695 EJ (Masters et al., 1994). The fraction of the CBM resource that can be recovered economically depends on both the quality and accessibility of the resource and the recovery technology employed.

CBM is recovered commercially in the US, mostly in the San Juan Basin of New Mexico and Colorado and the Black Warrior Basin of Alabama and Mississippi (McCabe et al., 1993). U.S. CBM production grew rapidly from about 40 billion standard cubic feet (bscf) (1.1 billion Nm^3) in 1988 to 350 bscf (9.4 billion Nm^3) in 1991 (McCabe et al., 1993) to 950 bscf (25.5 billion Nm^3) in 1996 (private communication from Karl Schultz, US EPA, 27 June 1997), when CBM production accounted for about 6% of total US natural gas production.

Current practice is to depressurize the coal bed (usually by pumping water out of the reservoir), which leads to desorption of the gas from the micropores of the coal matrix, its diffusion through the coal matrix to macrofractures in the coal called "cleats," and its flow

through the cleats to the wellbore for recovery (see Figure 4). The process is simple and effective but slow and inefficient; depressurization deprives the fluids of the energy to flow readily to the wellbore. There is typically a significant time lag (days to months) between the beginning of the dewatering process and the time when substantial gas recovery rates are realized.

USING CO_2 INJECTION FOR CBM RECOVERY AND THE COAL BED FOR CO_2 SEQUESTRATION

An alternative approach to CBM recovery that holds forth the prospect of being far more efficient is gas injection; for this purpose CO_2 is especially promising because it is twice as adsorbing on coal as CH_4; it can therefore efficiently displace the CH_4 adsorbed on the coal (Gunter et al., 1997). CO_2 injection makes it possible to maintain reservoir pressure and produce CH_4 gas quickly. As CO_2 moves through the reservoir it displaces CH_4; it has been found that very little of the injected CO_2 shows up in the production well until most of the CH_4 has been produced (Gunter et al., 1997). Thus the prospects for permanent sequestration of the injected CO_2 are good. Of course, sequestration of CO_2 in the coal bed would prevent subsequent mining of the coal. However, for much of the coal lying in deep beds that contain substantial quantities of CBM and that would be especially favorable sites for CO_2 sequestration mining the coal would be uneconomical.[8]

Although the recovery of coal bed methane (CBM) via CO_2 injection into deep coal beds is not yet commercial, the technology could be could be commercialized in five years or less if there were sufficient market interest (Williams, 1998).

The major challenge regarding this approach to CBM recovery is to have available a source of low-cost CO_2 at the prospective CBM recovery site.

AN OPPORTUNITY FOR LAUNCHING A CBM INDUSTRY IN CHINA USING BYPRODUCT CO_2 AT NH_3 PLANTS

China has a major opportunity to establish a CBM recovery industry based on CO_2 injection by locating plants for making NH_3 from coal near prospective CBM recovery sites and using the low-cost CO_2 produced as a byproduct of NH_3 production for stimulating the production of CBM.

When NH_3 is produced from a fossil fuel, a stream of CO_2 is produced as a byproduct.[9] In the case of NH_3 manufacture from coal the byproduct CO_2 generation rate amounts to somewhat

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[8] If all the world's estimated 85 to 262 trillion Nm^3 CBM resources could be exploited by CO_2 injection with sequestration of the injected CO_2, the global sequestration potential would be 90 to 280 GtC of CO_2. However, some of these resources will not be suitable for recovery via CO_2 injection, and some will be associated with minable coal resources, for which permanent CO_2 sequestration would probably not be considered.

[9] The stream of CO_2 is actually generated as a byproduct of the manufacture of the intermediate product H_2 in the amount 29.7 kgC per GJ of H_2 (0.71 kmol CO_2 per kmol H_2) produced from coal and 10.7 kgC per GJ of H_2 (0.25 kmol CO_2 per kmol H_2) produced from methane (Williams, 1996).

more than one kmol of CO_2 per kmol of NH_3. The amount of CO_2 potentially available for applications such as CBM recovery depends on the form of the fertilizer produced. If the desired product is ammonium nitrate, all the byproduct CO_2 is available. If instead the desired product is urea, about half the separated CO_2 is needed for urea manufacture.[10] In either case the excess CO_2 could be used for stimulating CH_4 recovery from deep beds of unminable coal, if such beds were located nearby.

In what follows the results of a study modeling systems of CBM recovery and use constructed in connection with the manufacture of NH_3 from coal are described. It is assumed that NH_3 manufacturing plants are located near sites with deep unminable coal deposits containing CBM. It is also assumed that the CBM resource characteristics are similar to those in CBM-rich areas of the San Juan Basin in the United States (Kuuskraa and Boyer, 1993).

Details of the calculations are presented elsewhere (Williams, 1998). For all cases, CBM recovery and use are considered in conjunction with the manufacture of 25.8 PJ (2.0 billion Nm^3) per year of H_2 from coal for fertilizer applications (ammonium nitrate in Cases Ia and IIa and urea in Cases Ib and IIb). It is assumed that the CBM resource is recovered over a 25-year period, the assumed lifetimes for the NH_3 production plants.

Two alternative uses of the recovered CBM are considered:

(*i*) *Case I*, for the production of additional H_2 feedstock for making more NH_3 and also providing more byproduct CO_2 for stimulating more CBM recovery [Case Ia for ammonium nitrate (NH_4NO_3) production (see Figure 5 and Table 1) and Case Ib for urea production (see Table 1)], and

(*ii*) *Case II*, for the production of electricity in a gas turbine/steam turbine combined cycle power plant [in conjunction with NH_4NO_3 production from coal in Case IIa (see Figure 6 and Table 2) and in conjunction with urea production from coal in Case IIb (see Table 2)].

In both instances production rates, costs, and CO_2 emission rates are compared to *Base Cases*, in which H_2 and electricity are produced from coal only with venting to the atmosphere of the CO_2

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[10] When NH_3 is used as a feedstock to produce urea for fertilizer, first CO_2 is reacted with NH_3 to form ammonium carbamate:

$$NH_3 + \tfrac{1}{2}\,CO_2 \rightarrow \tfrac{1}{2}\,NH_4COONH_2,$$

and then the ammonium carbamate is dehydrated to form urea (NH_2CONH_2):

$$NH_4COONH_2 \rightarrow NH_2CONH_2 + H_2O.$$

Because only about half of the available CO_2 is needed for the production of urea, the excess CO_2 could be used to stimulate CBM recovery from deep coal beds as an alternative to venting this CO_2 to the atmosphere, as is typically done today at urea plants.

produced in H_2 manufacture that is not used for urea manufacture (see Tables 1 and 2).

The systems described have scales that are consistent with modern coal production systems. For example, the largest CO_2 injection rate considered (Case Ia)[11] is 460 tonnes of CO_2/hour in Case Ia. This is approximately the CO_2 generation rate for a 500 MW_e coal steam-electric power plant. This case also involves the highest CBM production rate, some 37 PJ (920 million Nm^3) per year.

The CBM cost estimates summarized here and presented elsewhere (Williams, 1998) are in two parts:

(*i*) *CBM recovery cost estimates* by Kuuskraa and Boyer (1993) for conventional CBM recovery techniques, less the Kuuskraa/Boyer estimates of the costs for conventional (hydraulic) methods of stimulating CBM recovery, applied to CBM reservoirs similar to those in the CBM-rich parts of the San Juan Basin, plus

(*ii*) *costs for stimulating CBM recovery with CO_2 injection* [costs for CO_2 compression, transport, and injection, based on previous analyses relating to CO_2 sequestration in depleted natural gas fields (Blok et al. 1997) and aquifers (Hendriks, 1994), modified as appropriate to reflect assumed coal bed reservoir characteristics].

Because the use of CO_2 injection for CBM recovery is not yet commercial technology, and because costs will be very site specific [depending on the reservoir geometry, permeability (a measure of the ability of a gas to flow through the reservoir as a result of the structure and interconnection of the pore spaces), the placement and distribution of CO_2 injection wells and CBM recovery wells, etc.], the cost estimates presented here are very preliminary. However, because no increase in system productivity is assumed for CBM recovery with CO_2 injection compared to the use of conventional CBM recovery technology, the cost estimates presented here may well be overestimates.[12]

In Case Ia, it is assumed that the CBM is recovered from an array of 200 wells[13] in a circular field having an area of 130 km^2 (so that the recovery field area per CBM recovery well is 65 hectares), at the center of which the energy conversion facility is located. It is assumed that the wells are arranged such that aggregate output of all the wells can be maintained at a relatively constant level over the assumed 25-year life of the CBM recovery facility. With 200 wells the average CBM recovery rate is 12,700 Nm^3 (0.47 million scf) per day per well,[14] so that the

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[11] The smallest CO_2 injection rate considered (Case IIb) is 181 tonnes of CO_2/hour.

[12] In the CBM recovery cases discussed by Gunter et al. (1997) cumulative CBM recovery is enhanced by more than a factor of two with CO_2 injection and the CBM is produced much earlier with CO_2 injection compared to primary pressure depletion methods.

[13] The number of CBM wells is assumed to be proportional to the rate of CO_2 injection. Accordingly, there are 79, 154, and 82 CBM recovery wells for Cases Ib, IIa, and IIb, respectively.

[14] For comparison, at the end of 1991 there were 1660 CBM wells in the San Juan Basin producing CBM at

ultimate recovery is 1.78 million Nm^3 (66 million scf) per hectare.[15] It is assumed that the average well depth is 856 m [the average for all CBM wells drilled in the United States in 1990 (Petzet, 1991)], and that CBM well costs are the same as the average for all CBM wells drilled in the United States in 1990, some $291 per m (Petzet, 1991). Costs for CBM recovery per well other than for the recovery wells are assumed to be the same as costs estimated by Kuuskraa and Boyer (1993), except that hydraulic "well stimulation costs" as estimated by those authors are replaced here by costs for CO_2 compression, transport, and injection into the coal bed.

It is assumed that the CO_2 recovered at the H_2 production plants at 1.3 bar is compressed to 100 bar and transported by pipeline to the CO_2 injection sites. The CO_2 injection rate for a well (which determines the number and spacing of wells) is directly related to the reservoir thickness, its permeability, and the difference between the pressure at the bottom of the well and the reservoir pressure at a large distance from the well. For simplicity (and in the absence of any specific data for CBM reservoirs in China) it is assumed that the reservoir is a uniform, horizontal, 10-m thick coal bed,[16] that the coal bed permeability is 10 millidarcies,[17] and that the pressure difference between the well-bottom and the reservoir is 80 bar.[18] Under these conditions, the CO_2 injection rate per well would be about 28 tonnes of CO_2 per hour,[19] so that

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an average rate of 0.60 million scf per day per well (Kuuskraa and Boyer, 1993).

15 In the CBM-rich regions of the San Juan Basin the CBM resource in place is in the range 2 to 4 million Nm^3 per hectare (Kuuskraa and Boyer, 1993).

16 In the CBM-rich Fruitland Formation of the San Juan Basin coal bed thickness range between 6 and 24 m (Kuuskraa and Boyer, 1993).

17 A typical value for coal beds (Gunter et al., 1997). One millidarcie = 10^{-15} m^2.

18 The pressure at the well bottom is 99.5 bar (pressure at the wellhead) + (0.092 bar/m)*d, where d = well depth in meters (Hendriks, 1994) For the assumed value of d = 856 m, the pressure at the well bottom is 178 bar. Assuming a normal hydrostatic geopressure gradient of 115 bar per km, the reservoir pressure at 856 m is 98 bar. Thus the pressure difference is 80 bar.

19 The feasible CO_2 injection rate per well (and thus the number of injection wells needed) depends directly on the thickness of the coal bed and its permeability to the flow of CO_2. These parameters can be related by the following heuristic formula used by reservoir engineers (Hendriks, 1994):

$$q_s = 2\pi\,(\rho_r/\rho_s)\,kh\,\Delta P/[\,\mu \ln (r_e/r_w)],$$

where:

q_s = CO_2 flow rate [Nm^3/s],
ρ_r = CO_2 density under coal bed conditions = 700 kg/m^3 (typical value for supercritical CO_2),
ρ_s = CO_2 density under standard conditions = 1.97 kg/Nm^3,
k = permeability of the coal bed [m^2],
h = thickness of coal bed [m],
ΔP = difference between CO_2 pressures at the well bottom and at a long distance from the well [Pa],
μ = viscosity of the CO_2 at the well bottom = 6×10^{-5} Pa s (typical value),
r_e = radius of the influence sphere of the injection well [m],
r_w = radius of the injection well [m].

about 16 wells would be needed for Case Ia (i.e., there would be on average 12.5 CBM recovery wells per CO_2 injection well). Details of the cost estimates for CO_2 compression, CO_2 transport (16 pipelines of average length of 4.3 km), and CO_2 injection wells are presented in Williams (1998), drawn from Blok et al. (1997) and Hendriks (1994).

Results of the Case I analyses are presented in Table 1. In Case Ia the amount of H_2 derivable from CBM is 82% of what is produced in the Base Case; in Case Ib the amount of H_2 derivable from CBM is 17% of what is produced in the Base Case. The net lifecycle CO_2 emissions for CBM-derived H_2 are negative because all the costs for CO_2 injection and thus credit for the CO_2 sequestered are assigned to CBM production and thereby to the manufacture of H_2 from CBM. Emissions of CO_2 per GJ associated with H_2 manufacture from coal in Case I are also 1/3 less than in the Base Cases, because with CO_2 injection CBM (the use of which is characterized by negative net lifecycle CO_2 emissions) rather than coal is used to provide the external electricity (in a 45%-efficient[20] combined cycle) and heat (in an 85%-efficient boiler) needed to make H_2 from coal. The average net emission rate for the entire system of H_2 production from coal plus CBM is 6.0 kgC/GJ_{H2} (15% of the emission rate for H_2 production in the Base Case) for Case Ia and 19.0 kgC/GJ_{H2} (50% of the emission rate in the Base Case) for Case Ib.

Results of the Case II analyses are presented in Table 2. CBM production is adequate to support 50%-efficient combined cycles at scales of 485 MW_e and 248 MW_e in Cases IIa and IIb, respectively. The amount of electric generating capacity in excess of onsite needs (both for H_2 production from coal and for CBM recovery) that can be supported by the recovered CBM amounts to 336 MW_e in Case IIa and 120 MW_e in Case IIb. As in the case of CBM-derived H_2, the net lifecycle CO_2 emissions for CBM-derived electricity are negative; emissions of CO_2 associated with H_2 production from coal are also 1/3 less than in the Base Cases. The average net emission rate for the entire system of H_2 production from coal plus electricity production from CBM are, for Case IIa ¼ as much, and, for Case IIb ½ as much, as in the Base Cases (defined as producing from coal without CO_2 sequestration the same amounts of H_2 and electricity as in Cases IIa and IIb).

In all cases considered here the estimated CBM production cost is in the range \$1.7 to \$1.8 per GJ.[21] If these cost estimates prove to be reasonably good, CBM will come to be viewed as a very competitive[22] as well as a very clean energy source. At such CBM prices the estimated cost of the extra H_2 produced from CBM in Case Ia is about \$4.2/GJ_{H2}, some 60% of the cost of H_2 produced from \$1.0/GJ coal in the Base Case; in Case Ib the cost of CBM-derived H_2 is \$5.2/GJ_{H2}, about 70% of the cost of H_2 in the Base Case.

It is assumed that h = 10 m (see footnote 16), that $k = 10^{-14}$ m^2 (10 millidarcies) (see footnote 17), and that ΔP = 80 bar = 8,000,000 Pa (see footnote 18). Following Hendriks (1994), it is assumed that $\ln(r_e/r_w) = 7.5$. Thus the CO_2 flow rate assumed per well in the present analysis is $q_s = 3.97\ Nm^3/s$ = 28.2 tonnes/h.

20 All efficiencies presented in this paper are based on higher heating values (HHVs) for fuels.

21 Cost estimates and prices in this paper are in 1991 U.S. dollars.

22 For comparison, the average U.S. wellhead natural gas price (in 1991\$) in 1996 was \$1.80/GJ (EIA, 1997)

For cases IIa and IIb the estimated cost per kWh of the electricity produced in CBM-fired combined cycle plants is about 80% of the cost of producing electricity from \$1.0/GJ coal in steam-electric power plants in the Base Cases. Moreover, local air pollutant emissions would be much less, in light of the fact that electricity generated from natural gas in combined cycle power plants has the lowest local air pollutant emissions of all fossil fuel thermal-electric power generating technologies.

Cases I and II require comparable financial investments beyond the coal-related investments required (e.g., \$387 million for Case Ia[23] and \$438 million for Case IIa[24]). The total capital at risk, however, is greater for Case I than for Case II. In Case I, some of the extra capital equipment for making NH_3 out of the CBM-derived H_2 would be idled at high cost if there were substantial unexpected reductions in the CBM recovery rate. But in Case II, where much of the produced electricity is exported to the utility grid [70% of the electricity produced in Case IIa (see Figure 5) and 50% in Case IIb], unexpected shortfalls in CBM recovery could probably be readily compensated for by other underutilized electric generating capacity on the electric utility grid, so that the financial risks associated with the uncertainty in the CBM recovery rate would be much less; moreover, in Case IIa, CBM electricity would still be competitive with coal electricity if the combined cycle power plant capacity factor were reduced from the assumed 90% to about 50% (with the capacity factor of the coal plant fixed at 90%). Thus initially, until the technology of CBM recovery is well enough understood that there can be a high degree of confidence that steady CBM recovery rates can be sustained, Case II strategies might be favored over Case I strategies for utilizing the recovered CBM.

Once the technology for using CO_2 injection for stimulating CBM recovery is well established, the use of the CBM for the production of additional H_2 (Case I) should be considered wherever there is a sufficiently high market for H_2 (e.g., for extra NH_3 production in the near term or for fuel cell applications in the longer term), in light of the much lower cost of making H_2 from CBM than from coal. When the major market for the produced H_2 is fuel cells, the energy/material balances and costs will be very similar to those for Case Ia rather than Case Ib, since in this instance all the byproduct CO_2 can be injected into the coal bed for stimulating CBM recovery and CO_2 sequestration.

This analyses indicates not only that there are likely to be large local and global environmental benefits associated with CO_2-stimulated CBM recovery carried out in conjunction with the production of H_2 for ammonia manufacture from coal in China, but also that there are favorable prospects that CBM production carried out in this manner would be economically competitive in serving near-term H_2 or electricity needs. These findings highlight the importance of developing this CBM recovery technology quickly.

THE POTENTIAL FOR HYDROGEN DERIVED FROM COAL AND CBM FOR

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[23] \$152 million for CO_2 compression, transport, and injection; \$155 million for CBM recovery; and \$80 million for the combined cycle plant. See Williams (1998) for details.

[24] \$118 million for CO_2-related activities, \$120 million for CBM recovery; and \$200 million for the combined cycle plant.

;PORTATION APPLICATIONS IN CHINA

[he suitability of H_2 derived from coal plus CBM for use in fuel cell transportation ions in China as an alternative to the use of HC fuels in internal combustion engine depends on relative costs to the consumer, relative lifecycle emissions, and the adequacy rgeted energy resources in relation to future transportation needs.

For specificity in addressing these issues for China, calculations are presented relating to ive applications, even though other transport modes might prove to be more important in transport future. The automotive example is useful in testing the hypothesis that H_2 fuel 1 play major roles in transportation more generally, because cost, environmental impact, urce challenges are probably more daunting for automotive than for other modal ions.

Consumers

Hydrogen produced from coal and CBM will typically cost consumers more per GJ than ional HC fuels. For example, H_2 produced from coal plus CBM and transported more 00 km by long-distance H_2 pipelines to urban centers where it is distributed to H_2 g is estimated to cost consumers perhaps 1.8 to 1.9 times as much per GJ as the present ail gasoline price (excluding retail gasoline taxes).[25] However, it is expected that H_2 fuel s would be about 2.5 times as energy-efficient as gasoline internal combustion engine cars times as energy-efficient as gasoline fuel cell cars of comparable size and performance et al., 1997). Thus the cost of fuel per km of driving a H_2 fuel cell car would probably nore than for a gasoline internal combustion engine car, even if the world crude oil price t increase above its present very low level. The fuel cost per km for a H_2 fuel cell car be nearly ¼ more than for a gasoline fuel cell car at the present U.S. gasoline price. But this case, the H_2 fuel cell car would probably be less costly *on a lifecycle cost basis,* e the gasoline fuel cell car is expected to have a higher first cost than a H_2 fuel cell car 1 et al., 1997; Williams, 1997).

ions

Local air pollutant emissions from H_2 fuel cell vehicles would be zero without the use of e emission controls. Moreover, local pollutant emissions from H_2 production facilities probably be extremely low, even for the H_2 produced from coal. Experience with coal ted gasifier/combined cycle power plants has demonstrated emission levels about as low

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Consider H_2 derived from coal plus CBM (53% from coal, 47% from CBM) for transportation ions. For a scheme similar to that presented in Case Ia above the average production cost of H_2 is estimated .6/GJ (slightly less than the value of \$5.9/GJ indicated for Case Ia in Table 1 because for transportation ions the H_2 is assumed to be compressed only to 75 bar for transfer to the long-distance transmission line, ed to the 300 bar pressure required for ammonia manufacture). Hydrogen transport 1100 km to demand by transmission and distribution pipelines is estimated to add \$2.7/GJ and refueling stations \$4.2/GJ ns, 1997), bringing the total consumer price to \$12.5/GJ. For comparison, the U.S. retail gasoline price ing retail taxes) was \$6.7/GJ (89 cents/gallon or 23 cents/liter) in 1991, when the world oil price was less 9 per barrel.

as for natural gas-fired combined cycle power plants, which are the cleanest thermal power plants in use.

Lifecycle CO_2 emissions for the system of producing H_2 from coal plus CBM with sequestration of CO_2 in coal beds and using the H_2 in fuel cell cars are shown in Tables 3a and 3b. Lifecycle emissions *per GJ of fuel produced and used* are half as much for H_2 as for reformulated gasoline (see Table 3a).[26] Lifecycle emissions *per km of driving* H_2 fuel cell cars are expected to be only about 1/5 of those for gasoline internal combustion engine cars and 1/3 of those for gasoline fuel cell cars, when cars of the same size and performance are compared, because of the higher energy efficiency of the H_2 fuel cell cars (see Table 3b).

The combination of fuel cell cars and H_2 derived from coal plus CBM with coalbed sequestration of CO_2 technologies would give rise to CO_2 emissions per km so low that even if China should pursue a full-blown automotive culture with these technologies, the impact on global CO_2 emissions would be modest, as is illustrated by the following *gedanken* experiment. Suppose that by 2050: (*i*) there are 350 million fuel cell cars[27] in China fueled with H_2 produced this way, (*ii*) the average gasoline-equivalent fuel consumption rate of these cars is 2.35 liters/100 km or 100 mpg [which is likely to be typical for H_2 FC cars (Kreutz et al., 1996)], and (*iii*) these cars are driven on average 15,000 km per year. The lifecycle CO_2 emissions from this system would be about 46 million tonnes of carbon per year—equivalent to just 6% of CO_2 emissions by China and 0.8% of global CO_2 emissions from fossil fuel burning in 1990 (see Table 3b).[28]

Energy Resource Requirements

The *gedanken* experiment described above can also be used to illustrate the energy supply implications of adopting a H_2 fuel cell automotive strategy at large scale in China.

First consider the implications of an oil-based instead of a coal/CBM-based automotive strategy. If China were to support a fleet of 350 million gasoline-powered internal combustion engine cars having an average fuel use rate of 10.42 liters/100 km (or 22.6 mpg, the average fuel economy of passenger cars in the United States at present), total oil requirements for cars (~ 19 EJ/year or 8.5 million barrels per day—see Table 3c) would be equivalent to total U.S. oil imports in 1995 (EIA, 1997). Oil requirements would be less by nearly half if instead more fuel-efficient internal combustion engine cars were adopted or by a factor of three if gasoline fuel cell cars were pursued (see Table 3c). But automotive dependence on oil could be eliminated entirely

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[26] About 2/5 of the lifecycle emissions for H_2 production and use (see Table 3a) are associated with H_2 compression at refueling stations, assuming coal-derived electricity is used to drive the compressors. If low or zero carbon power sources were used instead, lifecycle emissions would be much lower than indicated in Table 3a.

[27] The number of family cars in China is projected to increase from 0.23 million in 1990, to 3.0 million in 2000, 10.0 million in 2010, and 40.0 million in 2020 (Li et al., 1995). If subsequently the growth rate were half the rate projected for the period 2010-2020, the number of cars in 2050 would be 350 million, so that at that time there would be 1 car for every 4.4 people in China.

[28] Total CO_2 emissions from all fossil fuel burning in China amounted to 720 million tonnes C/year in 1990 (Li et al., 1995), when global CO_2 emissions totaled 6000 million tonnes C/year.

if instead H_2 fuel cell cars were adopted, with H_2 derived from coal and CBM as described above.

The H_2 required to support a fleet of 350 million cars is 4.3 EJ/year; the corresponding amounts of coal and CBM needed to provide this much H_2 are 2.9 EJ/year and 3.3 EJ/year, respectively (see Table 3c). This rate of coal consumption is less than 13% of the rate of total coal use in China in 1990. Although this rate of CBM consumption is nearly five times the rate of natural gas consumption in China in 1990, CBM requirements are modest in relation to potential resources: a fleet of 350 million cars could be supported for 100 years with about 1/4 of the estimated CBM resources in China.

These calculations show that this automotive scenario would not be resource-constrained. Moreover, transportation strategies that emphasize instead buses and two- and three-wheeled vehicles, which are less energy-intensive than cars, would be even less resource-constrained. Although such alternatives to a high level of dependence on the automobile might be preferred in a country with a high population density such as China, they should be preferred because they would cause less congestion and noise or because adoption of the automobile culture would require sacrificing other development goals, not because of concerns about energy resource constraints—or concerns about local air pollution or greenhouse gas emissions.

CONCLUSION

There are powerful economic, energy security, and local, regional, and global environmental reasons why China should give serious attention to low-temperature fuel cells for transportation and stationary CHP applications. Moreover, the rapid growth in demand for transportation services from the present very low base level suggests an urgency for getting underway a transition to fuel cells in China, at least in the transport sector—in light of the scarcity of China's domestic oil resources and the prospect that world oil prices might be rising by the time oil begins to play a significant role in its energy economy, if China chooses to pursue an oil-intensive transportation strategy.

On the demand side, a transition to fuel cells might begin with commercial demonstration projects relating to the most important prospective fuel cell markets in China. Such demonstration projects should include both CHP and transportation applications, with emphasis on the latter, in light of the "window of opportunity" for leapfrogging over internal combustion engines to fuel cells in the transportation sector. Transportation demonstration projects should include urban buses (for which a demonstration project is already being planned), 2- and 3-wheel vehicles, locomotives, and trucks—important transport modes in China that are getting little attention in the industrialized countries, where attention is focused on the automobile.

A major option for China in providing H_2 fuel for PEM fuel cells would be to make H_2 from its abundant coal and CBM resources, using the CO_2 byproduct of H_2 production for stimulating CBM recovery. High priority should be given to demonstrating the technology of CBM recovery with CO_2 injection in China. Although on the basis of present knowledge it appears that China's CBM resources exploited in conjunction with its coal resources are likely to adequate to support a very large transportation system based on H_2 fuel cells, priority should also be given to estimating by region the extent of CBM resources that are economically recoverable

with this technique. Because it is already making H_2 from coal (using modern coal gasification technology) in the manufacture of ammonia for fertilizer applications, China does not have to acquire new foreign technology to create a H_2 industry for fuel cells. Moreover, China could launch such a H_2 production industry based on coal plus CBM even before fuel cells are commercially ready, because the H_2 so produced could be used initially in the fertilizer industry; in these applications, the extra H_2 that could be produced from the CBM would be less costly to make than the H_2 now produced from coal in the manufacture of ammonia for fertilizer applications.

Because the needed near-term activities on both the demand and supply sides could lead to substantial global benefits in the form of reduced greenhouse gas emissions as well as local and regional environmental and economic benefits, the (low-temperature fuel cell)/(coal/CBM-derived H_2 production) strategy outlined here involves bringing to market clusters of technology around which China should be able to find willing industrialized country partners, in light of the prospectively favorable economics and the need for industrialized country/developing country partnerships in meeting the objectives set forth in the Framework Convention on Climate Change (FCCC) and the urgency of creating such partnerships in light of the Kyoto Protocol that emerged from the Third Conference of the Parties to the FCCC.

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APPENDIX: OPTIONS FOR CO_2 STORAGE

Although disposal in the deep oceans is the most-discussed option for CO_2 disposal,[29] much more research is needed to better understand the security of various ocean disposal schemes and their environmental impacts (Turkenburg, 1992). In recent years increasing attention has been given to geological (underground) storage of CO_2: in depleted oil and natural gas fields (including storage in conjunction with enhanced oil and gas recovery), in deep saline aquifers, and in deep coal beds [in conjunction with coal bed methane (CBM) recovery].

Sequestration in depleted oil and gas fields is generally thought to be a secure option if the original reservoir pressure is not exceeded (van der Burgt et al., 1992; Summerfield et al., 1993). One estimate of the prospective sequestering capacity of oil and gas reservoirs associated with past production plus proven reserves plus estimated undiscovered conventional resources (most of which will be used up during the next century) is about 100 GtC for oil fields and about 400 GtC for natural gas fields (Hendriks, 1994); other estimates of the oil and gas field sequestering capacity are as low as 40 GtC for depleted oil fields plus 20 GtC associated with enhanced oil recovery plus 90 GtC for depleted natural gas fields (IPCC, 1996). (For comparison, global CO_2 emissions from fossil fuel burning totaled 6.0 GtC in 1990.) There is a considerable range of uncertainty in the global sequestering capacity of depleted oil and gas fields and the security of such sequestration. More research and field testing are needed to refine sequestering capacity estimates for depleted oil and gas fields, because reservoir properties vary greatly in their suitability for storage, and because the recovery of oil and gas from these reservoirs may have altered the formations and affected reservoir integrity. Although much of the prospective sequestering capacity will not be available until these fields are nearly depleted of oil and gas, CO_2 injection for enhanced oil recovery, which is established technology (Blunt et al., 1993), might become one focus of initial efforts to sequester in profitable ways CO_2 recovered in H_2 production.

Without the benefit of enhanced resource recovery, storage in aquifers will generally be more costly than storage in depleted oil or gas fields. However, deep saline aquifers are much more widely available than oil or gas fields; such aquifers underlie most sedimentary basins, which account for nearly half of the land area of the inhabited continents. To achieve high storage densities, CO_2 should be stored at supercritical pressures (i.e., at pressures in excess of 74 bar). Since the normal hydrostatic geopressure gradient is about 100 bar per km, typically depths of about 800 m or more are required for CO_2 sequestration in aquifers. The aquifers at such depths are typically saline and not connected to the much shallower (typically < 300 m) "sweetwater" aquifers used by people.

If aquifer storage is limited to closed aquifers with structural traps, the potential global

[29] The deep oceans represent a very large potential sink for anthropogenic CO_2. The ultimate sequestering capacity of the oceans (determined by choosing a nominal allowable change in the average acidity of all ocean water) has been estimated to the in the range 1,000 to 10,000 GtC, the equivalent of 200 to 2,000 years of emissions from fossil fuels (Socolow, 1997). If the injected CO_2 can be incorporated in the general oceanic deep water circulation, a residence time of up to 1,000 years can be anticipated.

sequestering capacity is relatively limited, some 50 GtC (Hendriks, 1994), equivalent to less than 10 years of global CO_2 production from fossil fuel burning at the current rate. However, if structural traps are not required for secure storage, the storage capacity of aquifers would be huge–some 14,000 GtC (Hendriks, 1994), equivalent to more than 2,000 years of CO_2 emissions from fossil fuel burning at the current global rate. A growing body of knowledge indicates that many large horizontal open aquifers might also provide secure storage if the CO_2 is injected far from the reservoir boundaries (Holloway, 1996). The notion that large horizontal aquifers can provide secure sequestration is a relatively new idea that has led to an increase in confidence that long-term sequestration of a significant fraction of the next several centuries of global CO_2 production from human activities may be feasible (Socolow, 1997; PCAST Energy R&D Panel, 1997).

Good estimates of the aquifer sequestration potential require considerable data gathering for and detailed modeling of specific aquifers. A recent major study carried out under the Joule II Non-Nuclear Energy Research Programme of the European Commission (Holloway, 1996) did a considerable amount of such modeling in an assessment of underground CO_2 storage reservoirs in Europe. This study estimated that the underground storage capacity accessible to the European Union plus Norway (mostly deep aquifers under the North Sea) would be adequate to store more than 200 GtC–storage capacity equivalent to 250 years of CO_2 emissions from all of OECD Europe at the current emission rate.

Experience with aquifer disposal will be provided by two projects involving injection into nearby aquifers of CO_2 separated from natural gas recovered from CO_2-rich gas reservoirs. One is a Statoil project begun in 1996 to recover 1 million tonnes of CO_2 per year from the Sleipner Vest offshore natural gas field in Norway (Kaarstad, 1992). The second, which will commence in about a decade, will involve the recovery of over 100 million tonnes per year (equivalent to about 0.5 percent of total global emissions from fossil fuel burning) from the Natuna natural gas field in the South China Sea (71% of the reservoir gas is CO_2) (IEA, 1996).

CO_2 sequestration in conjunction with CBM recovery is discussed in the main text of this paper.

REFERENCES

Blok, K., R.H. Williams, R.E. Katofsky, and C.A. Hendriks, 1997: Hydrogen production from natural gas, sequestration of recovered CO_2 in depleted gas wells and enhanced natural gas recovery. *Energy*, **22** (2-3), 161-168.

Blunt, M., F.J. Fayers, and F.M. Orr, Jr., 1993: Carbon dioxide in enhanced oil recovery. *Energy Conversion and Management*, **34** (9-11), 1197-1204.

Campbell, C.J., and J.H. Laherrere, 1998: The end of cheap oil. *Scientific American*, **278** (3), 78-83, March.

Dunnison, D.S., and J. Wilson: 1994: PEM fuel cells: a commercial reality. In: *A Collection of Technical Papers: Part 3, 29th Intersociety Energy Conversion Engineering Conference.* Monterey, CA, August 7-11, 1260-1263.

EIA (Energy Information Administration), 1997: *Annual Energy Outlook 1998, with Projections Through 2020*, DOE/EIA-0383(98), U.S. Department of Energy, Washington, DC, December.

EIA (Energy Information Administration), 1998: *International Energy Annual*, DOE/EIA-021 (96), U.S. Department of Energy, Washington, DC, February.

Gunter, W.D., T. Gentzix, B.A. Rottenfusser, and R.J.H. Richardson, 1997: Deep coalbed methane in Alberta, Canada: a fuel resource with the potential of zero greenhouse emissions. *Energy Convers. Mgmt.*, **38** (Suppl.), pp. S217-S222.

Hendriks, C.A., 1994: *Carbon Dioxide Removal from Coal-Fired Power Plants* Ph. D. thesis, Department of Science, Technology, and Society, Utrecht University, Utrecht, The Netherlands.

Holloway, S. (British Geological Survey), ed., 1996: *The Underground Storage of Carbon Dioxide*. Report prepared for the Joule II Programme (DG XII) of the Commission of the European Communities, Contract No. JOU2 CT92-0031, Brussels, February.

IEA (International Energy Agency), 1996: CO_2 capture and storage in the Natuna NG project. *Greenhouse Issues*, **22**, 1.

IPCC (Intergovernmental Panel on Climate Change), 1996: Chapter 19: Energy supply options. In: *Climate Change 1995_Impacts, Adaptations, and Mitigation of Climate Change· Scientific-Technical Analyses.* [Watson, R.T., M.C. Zinyowera, and R.H. Moss (eds.)]. Cambridge University Press, Cambridge and New York.

Kaarstad, O., 1992: Emission-free fossil energy from Norway. *Energy Convers. Mgmt*, **33** (5-8), 781-786.

Kassler, P., 1994: *Energy for Development*. Shell Selected Paper, Shell International Petroleum Company, London, England, November, 11 pp.

Kircher, R., S. Birkle, C. Noelscher, and H. Voigt, 1994: PEM fuel cells for traction: system technology aspects and potential benefits. Paper presented at Symposium on Fuel Cells for Traction Applications Royal Swedish Academy of Engineering Sciences, Stockholm, Sweden, 8 February.

Kreutz, T., M. Steinbugler, and J. Ogden, 1996: Onboard fuel reformers for fuel cell vehicles: equilibrium, kinetic and system modeling. Poster paper presented at the 1996 Fuel Cell Seminar, Orlando, Florida, 17-20 November.

Kuuskraa, V.A., and C.M. Boyer, II, 1993: "Economic and Parametric Analysis of Coalbed Methane," Chapter 17, pp. 373-394, in *Hydrocarbon from Coal, AAPG Studies in Geology No. 38*, American Association of Petroleum Geologists.

Li, Junfeng, T.M. Johnson, Changyi Zhou, R.P. Taylor, Zhiping Liu, and Zhongxiao Jiang, 1995: *Energy Demand in China: Overview Report, Subreport Number 2 in China: Issues and Options in Greenhouse Gas Emissions Control*, report prepared for the Industry and Energy Division of the World Bank, with support from the Global Environment Facility, February.

Little, A.D., 1995: *Fuel Cells for Building Cogeneration Application_Cost/Performance Requirements and Markets*. Final Report prepared for the Building Equipment Division, Office of Building Technology, U.S. Department of Energy, NTIS, Springfield, VA.

Mark, J., J.M. Ohi, and D.V. Hudson, 1994: Fuel savings and emissions reductions from light duty fuel-cell vehicles. In: *A Collection of Technical Papers: Part 3, 29th Intersociety Energy Conversion Engineering Conference*. Monterey, CA, 7–11 August, pp. 1425–1429.

Masters, C.D., E.D. Attanasi, and D.H. Root, 1994: World petroleum assessment and analysis. *Proceedings of the 14th World Petroleum Congress*. Stavanger, Norway.

McCabe, P.J., D.L. Gautier, M.D. Lewan, and C. Turner, 1993: *The Future of Energy Gases*. U.S. Geological Survey Circular 1115, United States Government Printing Office, Washington, D.C.

Mitchell, W.L., J.H.J. Thijssen, J.M. Bentley, and N.J. Marek, 1995: Development of a catalytic partial oxidation ethanol reformer for fuel cell applications. *Proceedings of the 1995 SAE Alternative Fuels Conference*. SAE Technical Paper Series 952761, pp. 209-217.

Ogden, J., M. Steinbugler, and T. Kreutz, 1997: Hydrogen as a fuel for fuel cell vehicles: a technical and economic comparison. Presented at the 8th Annual Conference of the National Hydrogen Association, Arlington, VA, 11-13 March.

PCAST Energy R&D Panel, 1997. Federal Energy Research and Development for the Challenges of the Twenty-First Century. Report of the Energy Research and Development Panel of the President's Committee of Advisors on Science and Technology (PCAST), November. Available at http://www.whitehouse.gov/WH/EOP/OSTP/html/OSTP_Home.html on the World

Wide Web.

Petzet, G.A., 1991: "JAS Pinpoints Cost of Drilling U.S. Wells," *Oil & Gas Journal*, p. 30, 30 December.

Prater, K., 1996: Solid polymer fuel cells for transport and stationary applications. *Journal of Power Sources*, **61**, 105-109.

Rice, D.D., B.E. Law, and J.L. Clayton, 1993: Coal-bed gas–an undeveloped resource. In *The Future of Energy Gases*. U.S. Geological Survey Professional Paper No. 1570. United States Government Printing Office, Washington, DC, pp. 389-404.

Ross, M., R. Goodwin, and R. Watkins (Physics Department, University of Michigan), M.Q. Wang (Argonne National Laboratory), and T. Wenzel (Lawrence Berkeley Laboratory), 1995: *Real-World Emissions from Model Year 1993, 2000, and 2010 Passenger Cars*, American Council for an Energy-Efficient Economy, Washington, D.C., November.

Shell International Petroleum Company, 1995: *The Evolution of the World's Energy System 1860-2060*. Shell Centre, London, December.

Socolow, R.H., ed., 1997: *Fuels Decarbonization and Carbon Sequestration: Report of a Workshop by the Members of the Report Committee*. PU/CEES Report No. 302, Center for Energy and Environmental Studies, Princeton University, Princeton, NJ, September. This report is available on the World Wide Web at http://www.princeton.edu/~ceesdoe

SSB (State Statistical Bureau of the People's Republic of China), 1993: China Statistical Yearbook 1993, International Center for the Advancement of Science and Technology, Beijing, China.

Summerfield, I.R., S.H. Goldhorpe [British Coal Corporation, Coal Research Establishment], N. Williams, and A. Sheikh [Bechtel, Ltd], 1993: Costs of CO_2 disposal options. Paper presented at IEA Carbon Dioxide Disposal Symposium, Christchurch College, Oxford, England, 29-31 March.

Todd, D.M., and H. Stoll, 1997: Integrated gasification combined cycle–the preferred power technology for a variety of applications. Paper presented at Power-Gen Europe '97, Madrid, Spain, June.

Turkenburg, W.C., 1992: CO_2 removal: some conclusions. In: *Proceedings of the First International Conference on Carbon Dioxide Removal*. [Blok, K., W. Turkenburg, C. Hendriks, and M. Steinberg, (eds.)]. *Energy Conversion and Management*, **33** (5-8). 819-823. Pergamon Press, Oxford.

UNEP/WHO (United Nations Environment Programme/World Health Organization), 1992: In *Expanding Environmental Perspectives—Lessons of the Past, Prospects for the Future*, Department of Environmental and Energy Systems Studies, Lund University Press, Lund,

Sweden.

van der Burgt, M.J., J. Cantle, and V.K. Boutkan, 1992: Carbon dioxide disposal from coal-based IGCCs in depleted gas fields. In: *Proceedings of the First International Conference on Carbon Dioxide Removal.* [Blok, K., W. Turkenburg, C. Hendriks, and M. Steinberg, (eds.)]. *Energy Conversion and Management*, **33** (5-8), 603-610. Pergamon Press, Oxford.

Williams, R.H. 1993: Fuel cells, their fuels, and the U.S. automobile. In: *Proceedings of the First Annual World Car 2001 Conference*, University of California at Riverside, Riverside, CA.

Williams, R.H., 1994: Fuel cell vehicles: the clean machine. *Technology Review*, April, 21-30.

Williams, R.H., 1996: *Fuel Decarbonization for Fuel Cell Applications and Sequestration of the Separated CO_2.* PU/CEES Report No. 295, Center for Energy and Environmental Studies, Princeton University, Princeton, NJ.

Williams, R.H., 1997: Successful commercialization of fuel cell cars as a driver for H_2 infrastructure development. Paper prepared for the Workshop on Technological Opportunities for Fuels Decarbonization and Carbon Sequestration, Washington, D.C., July.

Williams, R.H., 1998: Hydrogen production from coal and coal bed methane, using byproduct CO_2 for enhanced methane recovery, with CO_2 sequestration in the coal bed. Draft manuscript, Center for Energy and Environmental Studies, Princeton University, Princeton, New Jersey, USA, 7 March.

Williams, R.H., E.D. Larson, R.E. Katofsky, and J. Chen, 1995a: Methanol and hydrogen from biomass for transportation. *Energy for Sustainable Development,* **1** (5), 18-34.

Williams, R.H., E.D. Larson, R.E. Katofsky, and J. Chen, 1995b: *Methanol and Hydrogen from Biomass for Transportation, with Comparisons to Methanol and Hydrogen from Natural Gas and Coal.* PU/CEES Report No. 292, Center for Energy and Environmental Studies, Princeton University, Princeton, NJ, July.

WRI (World Resources Institute), 1994: World Resources 1994-15: A Guide to the Global Environment, Oxford University Press, New York.

Table 1. Alternative Schemes for Producing H_2 for Fertilizer Manufacture in Coal-Rich Countries

	Base Cases. H_2 from Coal for Fertilizer Manufacture (Base Cases)[a]		*Case Ia*: H_2 from Coal + CBM for NH_4NO_3 Manufacture (CBM Produced by Injecting into Deep Coal Beds CO_2 Generated in Making H_2)[b]			*Case Ib*: H_2 from Coal + CBM for Urea Manufacture (CBM Produced by Injecting into Deep Coal Beds CO_2 Generated in Making H_2)[b]		
	NH_4NO_3 Production	Urea Production	H_2 from Coal	H_2 from CBM	H_2 from Coal + CBM	H_2 from Coal	H_2 from CBM	H_2 from Coal + CBM
Coal consumption rate (PJ/y)	42.83		33.28	-	33.28	33.28	-	33.28
CBM consumption rate (PJ/y)	-		8 43	28.30	36.73	8.43	6.00	14.43
H_2 production rate (PJ/y)	25.76		25.76	21 12	46.88	25.76	4.48	30 24
CO_2 available (kgC/GJ)	29.70	15 69	29.70	10 69	21.14	15 69	- 3.32	12 87
Use of available CO_2?	Vented to Atmosphere		Injected into Deep Coal Beds to Stimulate Production of CBM					
Coal price ($/GJ)	1 0							
CBM production rate (PJ/y)	-		36 73			14.43		
CBM production cost ($/GJ)[c]	-		1.80			1.72		
H_2 production cost ($/GJ)[d]	7.34		7.23	4.24	5.88	7.20	5.20	6.90
CO_2 emission rate (kgC/GJ)[e]	38.62		25.62	- 17.97	5.98	25.62	- 17.97	19.16

[a] In the Base Cases coal is used both as a feedstock and for providing external electricity (@ 35.5% efficiency) and heat requirements (@ 80% efficiency) in the manufacture of H_2.

[b] In these cases (Case Ia is shown in Figure 5) 85%-efficient CBM boilers are used to provide the external heat and 45%-efficient CBM-fired combined cycles are used to provide the external electricity required in H_2 manufacture from both coal and CBM, and coal is used only as a feedstock in the manufacture of H_2 from coal.

[c] The CBM production cost is developed in Williams (1998) for Case Ia, where CO_2 generated in making H_2 from coal is injected into the coal bed at a rate of 29.70 kgC/GJ_{H2} (NH_4NO_3 fertilizer production case) and the CBM production rate is 36.73 PJ/y; the same procedure is followed for Case Ib.

[d] The costs for producing H_2 pressurized to 300 bar from coal only (Base Case) and from CBM for Case Ia (where the H_2 is used to make NH_4NO_3 fertilizer) are developed in Williams (1998). The cost of producing H_2 from CBM is much higher for the urea production case (Case Ib) because of the scale economy effect at the lower CBM-derived H_2 production rate (4.48 PJ/y vs. 21.12 PJ/y), which arises because with urea production far less CO_2 is available for injection into the coal bed and thus far less CBM can be recovered and converted to H_2.

[e] The CO_2 emissions rates for burning coal and CBM are 23.23 kgC/GJ_{COAL} and 13.57 kg C/GJ_{CBM}, respectively. However, because costs associated with CO_2 sequestration are allocated to the cost of CBM production, credit for the CO_2 sequestered in the deep coal bed is assigned to CBM consumption at a rate of 26 98 kg C/GJ, so that the net emissions associated with CBM consumption 13.57 - 26.98 = - 13.41 kgC/GJ_{CBM}.

Table 2. Alternative Schemes for Producing Electricity In Conjunction with the Manufacture of Fertilizer from Coal-Derived H_2

	Base Cases: H_2 from Coal for Fertilizer Manufacture + Coal Steam-Electric Power[a]		*Case IIa*: H_2 from Coal for NH_4NO_3 Manufacture + CC CBM Power (CBM Produced by Injecting into Deep Coal Beds CO_2 Generated in Making H_2)[a]	*Case IIb*: H_2 from Coal for Urea Manufacture + CC CBM Power (CBM Produced by Injecting into Deep Coal Beds CO_2 Generated in Making H_2)[a]
	NH_4NO_3	Urea		
Coal consumption rate (PJ/y)	69.87	52.45	33.28	
CBM use in producing H_2 from coal (PJ/y)	-		7.59	
CBM use in external electricity generation (PJ/y)	-		20.77	7.39
Rate of producing H_2 from coal (PJ/y)	25.76			
CO_2 available (kgC/GJ_{H2})	29.70	15.69	29.70	15.69
Use of available CO_2?	Vented to Atmosphere		Injected into Deep Coal Beds to Stimulate Production of CBM	
CBM production rate (PJ/y)	-		28.36	14.98
Electricity production rate (TWh/y)	3.509	1 792	3 824	1.958
Rate of electricity export (TWh/y)	2.666	0.949	2.666	0.949
Coal price ($/GJ)	1.0			
CBM production cost ($/GJ)[b]	-		1.78	1.75
H_2 production cost ($/GJ)[c]	7.34		7.17	7.16
Electricity production cost (cents/kWh)[d]	2.82		2.23	2.20
CO_2 emissions, H_2 production (kgC/GJ)[e]	38.63		26.06	
CO_2 emissions, electricity generation (grC/kWh)[e]	235.6		- 104.5	
System CO_2 emissions (10^6 kgC/y)[e]	1623	1218	393	572

[a] In the Base Cases coal is used both as feedstock and for providing external electricity (@ 35.5% efficiency) and heat (@ 80% efficiency) requirements in H_2 manufacture. In the other cases (Case IIa is shown in Figure 6) 85%-efficient CBM boilers are used to provide the external heat and 50.2%-efficient CBM-fired combined cycles are used to provide the external electricity required in H_2 manufacture, and coal is used only as a feedstock.

[b] The CBM production cost is developed according to the procedure presented in Williams (1998).

[c] For H_2 pressurized to 300 bar. See Williams (1998) for the Base Case calculation. Costs are somewhat lower for the other cases because the required electricity is provided by CBM combined cycle plants at lower cost than for coal steam-electric plants.

[d] Assumed installed capital costs [$963/kW$_e$ for coal steam-electric plants and $413/kW$_e$ for CBM combined cycle (CC) plants] and O&M costs ($0.0041/kWh for coal steam-electric plants and $0.0035/kWh for CBM CC plants) are from a recent General Electric study (Stoll and Todd, 1997). Capital charge rates of $0.0140/kWh for coal steam-electric plants and $0.0060/kWh for CBM CC plants are calculated assuming these capital costs, a 10% discount rate, a 25-year plant life, a 0.5%/year insurance charge, and a 90% capacity factor.

[e] As in Table 1 (footnote e), net lifecycle CO_2 emission rates are 23.23 kgC/GJ_{COAL} and – 13.14 kgC/GJ_{CBM}.

Notes for Table 3, cont.

[e] The emissions are less than the 5.98 kgC/GJ_{H2} value for the case presented in Table 1, in which the H_2 recovered from the PSA unit at 20.3 bar is compressed to 300 bar for NH_3 production; for transportation applications it is assumed that the H_2 is compressed to 75 bar for transfer to long-distance pipeline transmission lines (Williams, 1997); as a result electricity requirements for H_2 compression are reduced from 8.42 to 3.94 kWh/GJ_{H2}, and lifecycle CO_2 emissions are reduced by 0.47 kgC/GJ_{H2}.

[f] At the refueling station H_2 is compressed from 200 psia (14 bar) to 6000 psia (414 bar) for storage before transfer to storage canisters onboard vehicles at 5000 psia (345 bar). Assuming 55%-efficient compressors, the required electricity is 18.86 kWh/GJ_{H2} (Williams, 1997). It is assumed that this electricity is provided by 35.5%-efficient coal-fired power plants and that the carbon content of coal is 23.23 kgC/GJ.

[g] For cars driven 15,000 km per year

[h] ICE = internal combustion engine, FC = fuel cell.

[i] The energy content of gasoline is 34.8 MJ/liter (0.132 GJ/gallon), HHV basis.

[j] This is the average rate of fuel use for U.S. passenger cars in 1995 (EIA, 1997).

[k] This ICE car and the gasoline and H_2 FC cars are assumed to have the same low load characteristics (lower rolling resistance, aerodynamic drag, and less weight than the average U.S. car in 1995) and performance (the same as for the average U.S. car in 1995). H_2 fuel cell cars are expected to be 2.5 times as energy-efficient as comparable ICE cars and 1.5 times as energy-efficient as gasoline fuel cell cars equipped with onboard partial oxidation fuel processsors (Ogden et al., 1997)

[l] For the lifecycle CO_2 emission rates per GJ presented in Table 3a.

[m] The energy use at the refinery is for reformulated gasoline, as estimated for U.S. refineries by DeLuchi (1991). China might use more coal instead of natural gas (NG) to meet refinery energy needs. If coal were substituted for NG at the same efficiency, lifecycle emissions for reformulated gasoline would increase 7%, actual emissions would probably increase more than this, because NG can generally be used more efficiently than coal.

[n] If the coal required to provide electricity for H_2 compressors at the refueling stations were included, total coal requirements for fuel cell cars would be 28% higher than indicated in Table 3c.

Table 3a: Lifecycle CO_2 Emissions from Production and Use of Alternative Tranportation Fuels (*kg C/GJ*)

	Reformulated Gasoline Derived from Crude Oil[a]	H_2 Derived from CBM + Coal with CO_2 for CBM Recovery & CO_2 Sequestration in Coal Beds[b,c]
Natural gas well CO_2	-	0.16 (CBM)
Feedstock recovery	0.56	0.21 (CBM) + 0.18 (coal)
Feed production	-	0.19 (CBM)
CBM feedstock transport	0.26	-[d]
Fuel production	3.24	5.51[e]
Fuel transport to refueling station	0.18	-
Compressors at refueling stations	-	4.44[f]
End use	18.40	0.00
Total	22.64	10.69

Table 3b: Lifecycle CO_2 Emissions for Fleet of 350 Million Cars with Alternative Engines and Fuels[g]

Automotive engine[h]	ICE	ICE	FC	FC
Gasoline-equivalent rate of fuel use, liters/100 km (mpg)[i]	10.42 (22.6)[j]	5.88 (40)[k]	3.53 (67)[k]	2.35 (100)[k]
CO_2 emissions, MtC/year[l]	431.5	234.4	140.6	46.0

Table 3c: Annual Energy Requirements for Fleet of 350 Million Cars with Alternative Engines and Fuels[g]

Final Energy Use Rate, EJ/year	19.1	10.8	6.5	4.3
Primary Energy Use Rate in Fuel Production, EJ/year	19.1 (oil) 1.1 (coal) 2.7 (NG)[m]	10.8 (oil) 0.6 (coal) 1.6 (NG)[m]	6.5 (oil) 0.4 (coal) 0.9 (NG)[m]	2.9 (coal)[n] 3.3 (CBM)

[a] Source: Williams et al. (1995a; 1995b).

[b] H_2 derived from CBM accounts for 47.3% of total H_2, slightly more than the 45.1% of Case Ia (Table 1); in the present case less electricity is needed for H_2 compression (see note e below), so that slightly more CBM is available as a feedstock for H_2 production.

[c] Emissions estimates for activities upstream of the H_2 production plant are from Williams et al. (1995a; 1995b).

[d] The emissions from the transport of CBM from the CBM production wells to the H_2 production facility are included in the emissions associated with H_2 production.

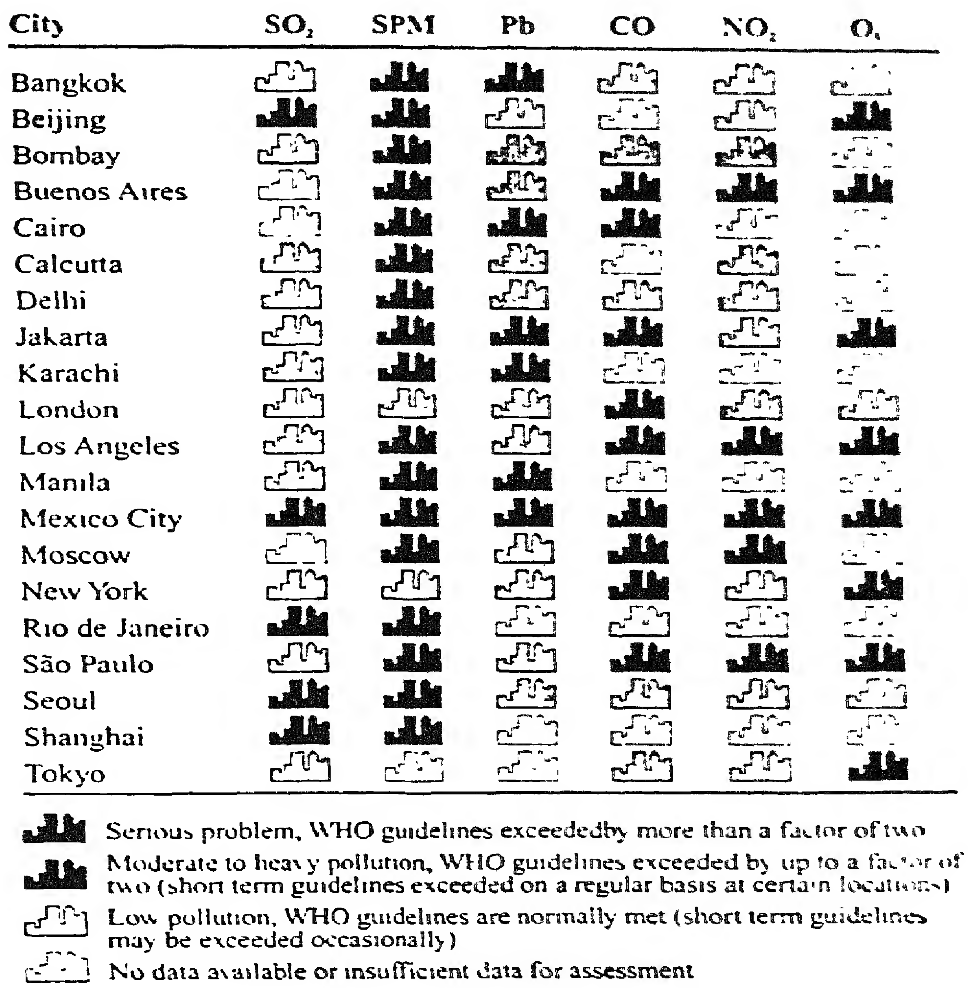

Figure 1: Overview of Air Quality in Twenty Megacities

These indicators are based on a subjective assessment of monitoring data and emissions inventory.

Source: UNEP, WHO (1992).

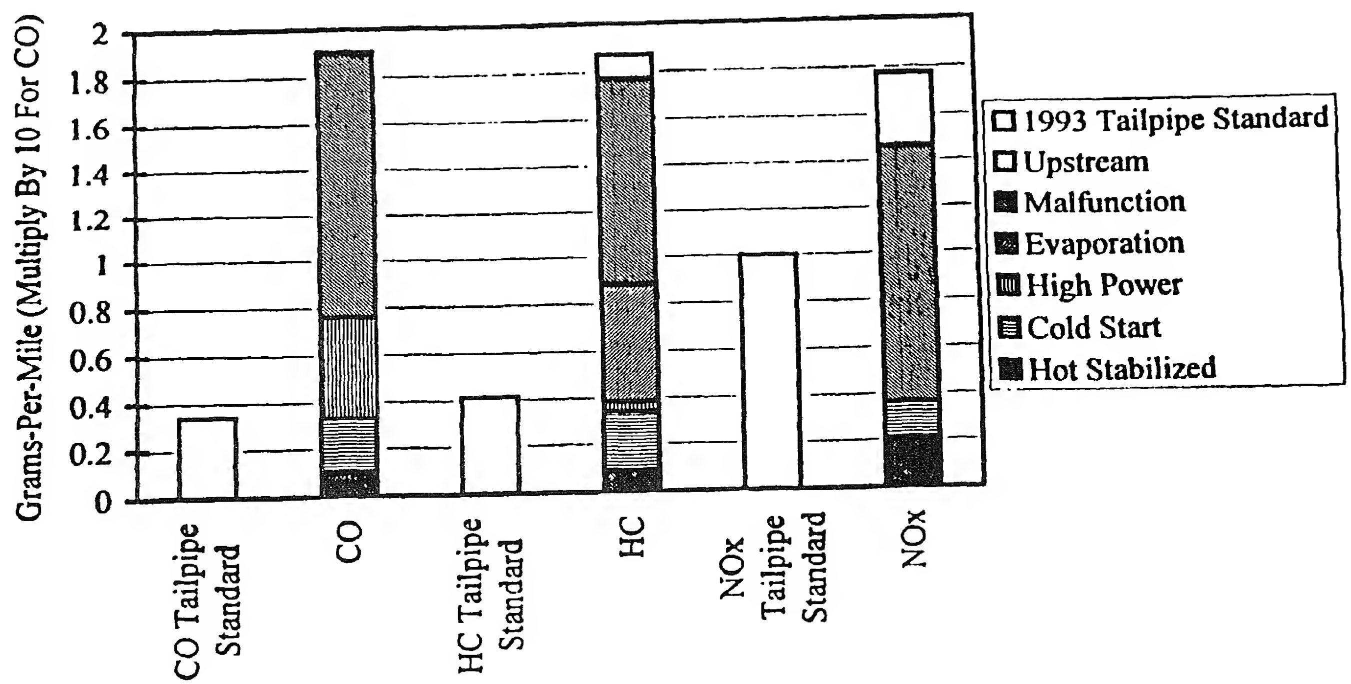

Figure 2: Expected Lifetime Criteria Pollutant Emissions for a US 1993-Vintage Passenger Car Compared to the Tailpipe Emission Standards for these Criteria Pollutants

Over the lifetime of a motor vehicle the actual emissions of critieria pollutants are far higher than the tailpipe emissions standards in the US because: (*i*) pollution control devices are designed to meet the performance levels specified in a test which does faithfully reflect real-world operating conditions, (*ii*) pollution control equipment sometimes malfunctions, and (*iii*) some emissions come from sources other than the tailpipe (evaporative emissions from the fuel tank, and emissions from the fuel production and delivery system upstream of the motor vehicle).

Source: (Ross et al., 1995).

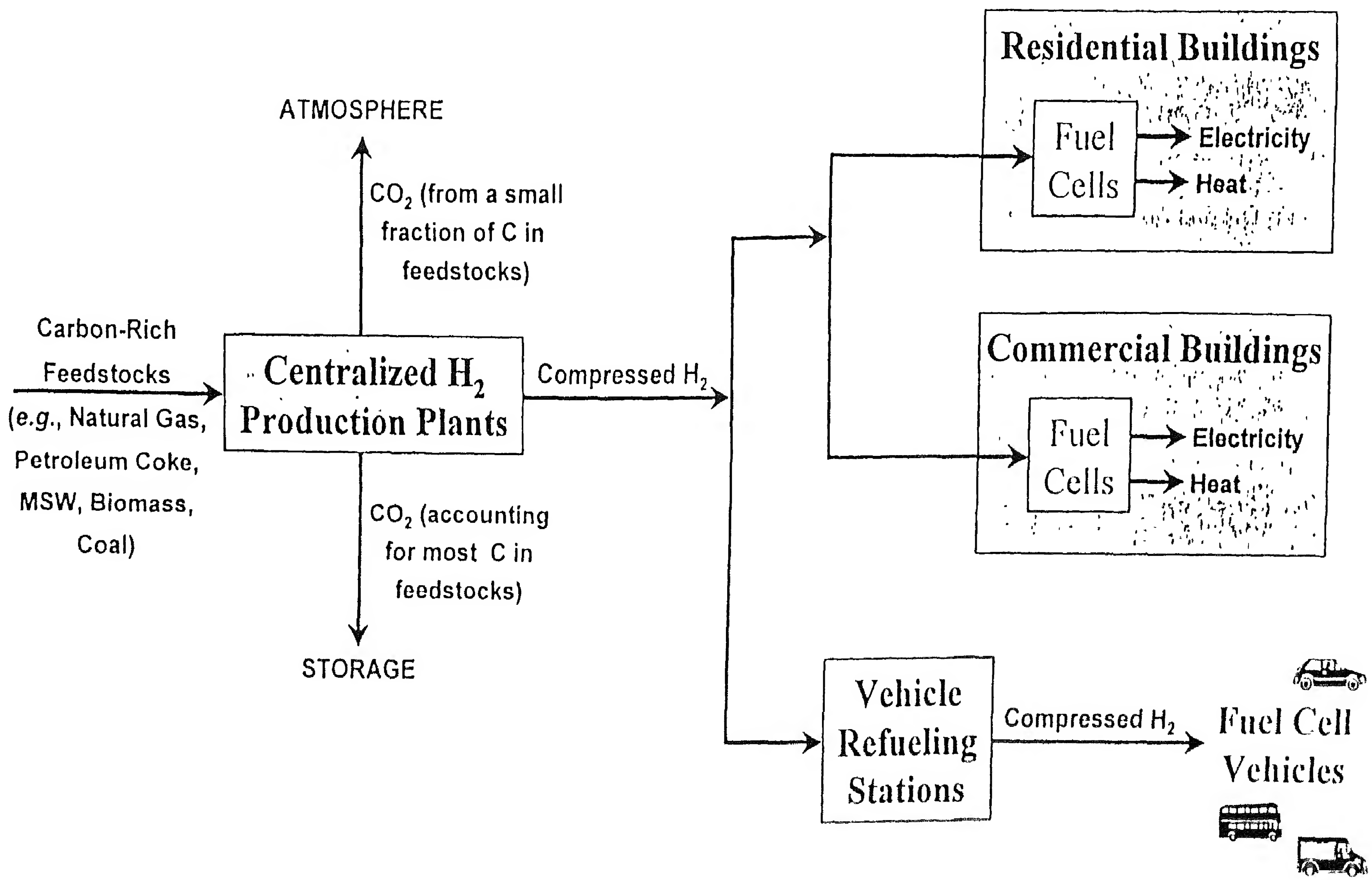

Figure 3: System for Hydrogen Production and Use for Transportation and Distributed Combined Heat and Power if Low Temperature Fuel Cells are Successfully Commercialized

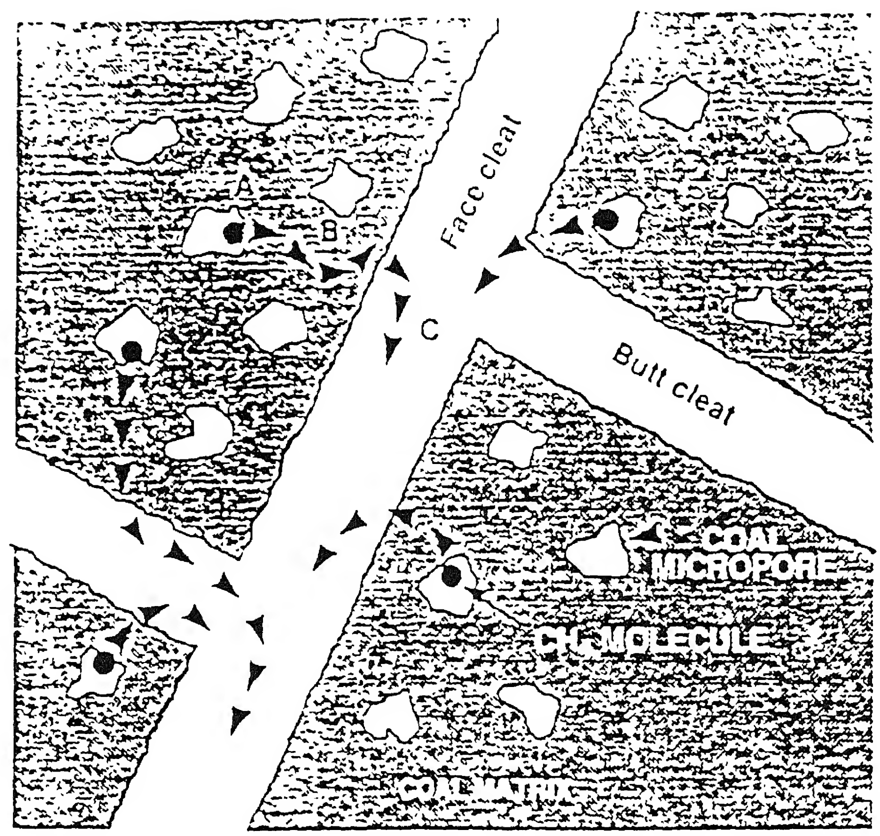

Figure 4: Diagram Showing (A) Desorption of Methane from Micropores in Coal As a Result of Reservoir Depressurization, (B) Diffusion Path of Methane Through the Coal Matrix, and (C) Flow of Methane in Through Fractures in the Coal Bed

Source: Rice et al. (1993).

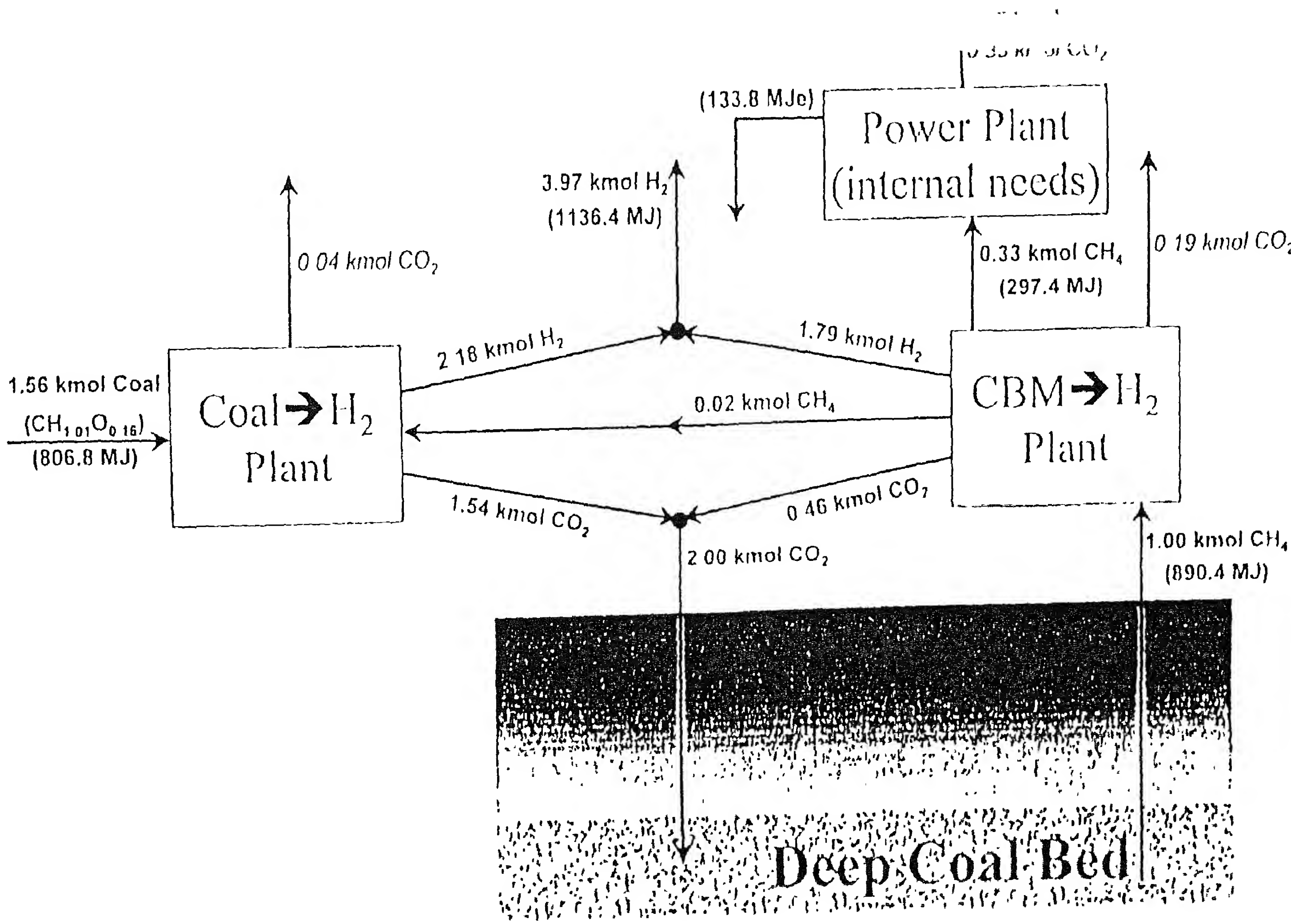

Figure 5: Material and Energy Balances for H_2 Production from Coal and Coal Bed Methane (CBM), Using All the CO_2 Separated at the H_2 Production Plant to Recover CBM, with Sequestration of the Injected CO_2 in the Coal Bed

For H_2 compressed to 300 bar, as would be required for ammonia manufacture. These balances (per kmol of CBM recovered from the coal bed) are for Case Ia in Table 1. The ratio of H_2 produced from the CBM feedstock to that produced from coal is for the situation where a 2/1 molar ratio for CO_2 injection to CBM recovery is realized. Some of the recovered CBM is used to provide the electricity needed to make H_2 from coal and CBM, to provide the electricity needed for CBM recovery, and to provide the external heat needed in the manufacture of H_2 from coal.

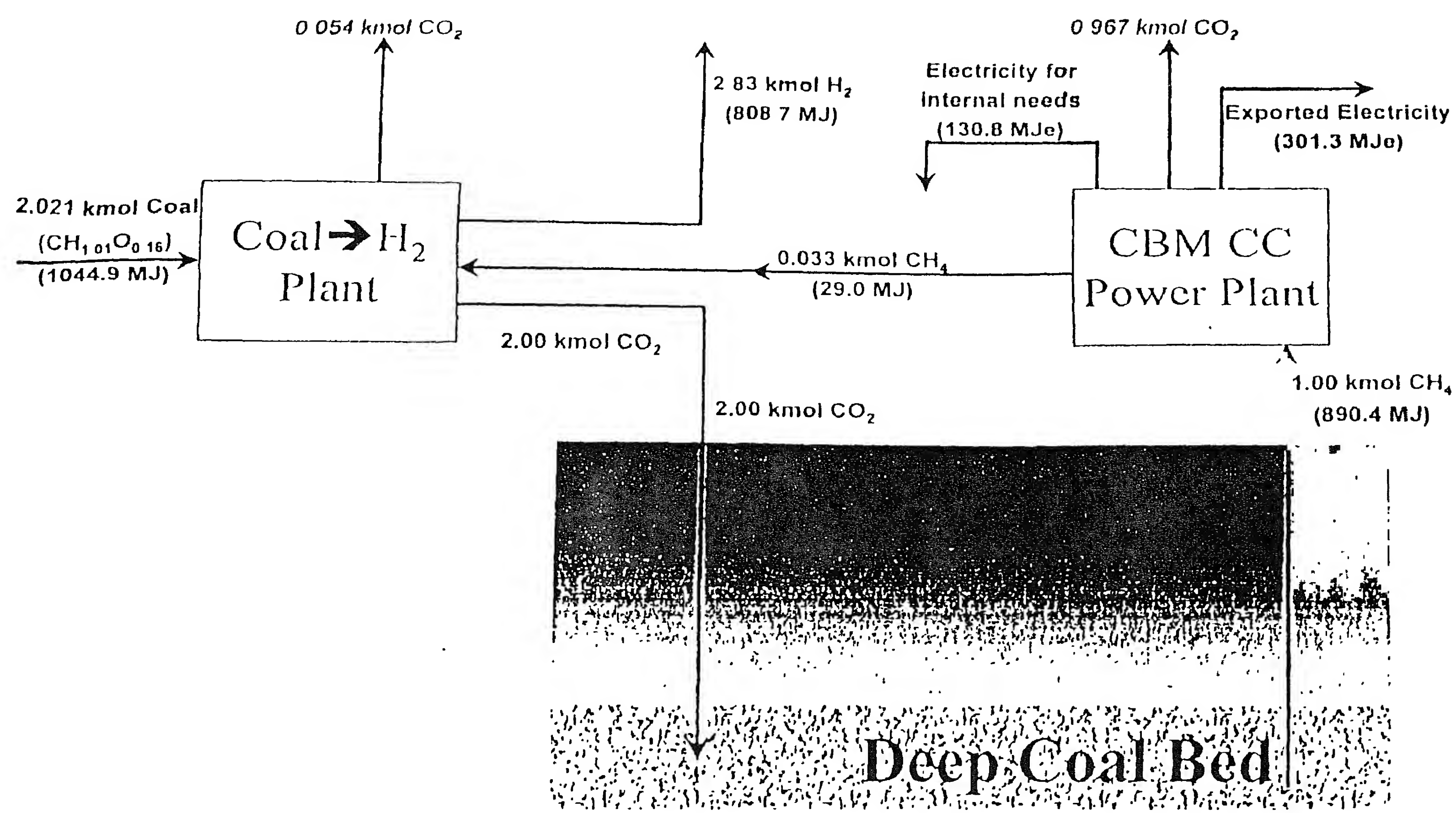

Figure 6: Material and Energy Balances for H_2 Production from Coal + Electricity Generation from CBM in a Combined Cycle Power Plant, Using the CO_2 Separated at the H_2 Production Plant to Recover CBM, with Sequestration of the Injected CO_2 in the Coal Bed

For H_2 compressed to 300 bar, as would be required for ammonia manufacture. These material and energy balances (per kmol of CBM recovered from the coal bed) are for Case IIa in Table 2. The ratio of H_2 production from the coal feedstock to the electricity production from CBM is for the situation where a 2/1 molar ratio for CO_2 injection to CBM recovery is realized. Some of the recovered CBM is used to provide the electricity needed to make H_2 from coal and CBM, to provide the electricity needed for CBM recovery, and to provide the external heat needed in the manufacture of H_2 from coal; the rest of the recovered CBM is used to make electricity for export from the site.